# Enhancing Athlete Profiling Through Technology-Integrated Multiple Hop Testing: Implications for Physiotherapy and Strength and Conditioning

## Anthony Peter Sharp

*A research component submitted to Auckland University of Technology in fulfilment of the requirements of the degree of*

**Doctor of Philosophy (PhD)**

**2025**

Primary Supervisor: Professor John Cronin
Secondary Supervisor: Dr Jonathon Neville

School of Sport, Exercise and Health
Sports Performance Research Institute New Zealand (SPRINZ)

# ABSTRACT

Multiple hop tests, such as the triple hop (TH) and quintuple hop (QH), are commonly used in strength training, conditioning, and physiotherapy to evaluate lower-limb function, monitor return-to-sport (RTS) progress, and measure athletic performance. Traditionally, these tests quantify total distance jumped, which offers limited insight into movement strategies. Advances in affordable technology, including smartphone videography to computer vision tracking, present opportunities to improve the diagnostic value of these assessments, but their validity, reliability, and practical usefulness are still under-investigated. Given this information, this thesis addressed the overarching question: can technology integration into multiple hop testing provide greater diagnostic insight to better inform physiotherapeutic and strength and conditioning practices? To answer this, the work was structured across four sections, each targeting a specific set of research questions.

The current literature on TH and QH tests was reviewed in Section 1, evaluating their reliability, utility, and relationship to performance. Findings highlighted that while the TH is reliable and commonly used, the QH remains under-researched, with limited evidence on its validity and sensitivity. Furthermore, reliance on distance as the sole outcome measure limited diagnostic value, underscoring the need for alternative metrics and accessible technologies to capture movement strategies.

The feasibility of smartphone videography for assessing multiple hop performance was investigated in Section 2. Using free software (Kinovea) with tablets and smartphones, strong between-rater (ICC = 0.85-1.00), within-rater (ICC = 0.98-1.00), and test–retest (ICC = 0.47-0.93) reliability for spatiotemporal variables such as flight time, ground contact time, and total time were found. High

levels of agreement were found when these variables were compared to gold standard force plates, although small systematic biases were observed. It was established that smartphone-based approaches provided valid, reliable, and cost-effective alternatives for hop diagnostics in field and clinical environments.

In Section 3, the physical and biomechanical demands of TH and QH tests, inter-limb asymmetries, and their relationship to sprint performance were explored. Successive hops imposed progressively greater eccentric braking demands, with vertical braking impulses increasing by ~32% and horizontal braking impulses by ~56%, highlighting the importance of graded progression in rehabilitation contexts. Kinetic analyses showed average asymmetries of up to 40% in braking impulses, with some reaching 96%. These asymmetries are often hidden when only using distance outcomes, which averaged 4.7% and peaked at 12.7%. Hop distances correlated strongly with 10-40 m sprint times ($r$ = 0.70-0.80), with reactive strength index horizontal ($RSI_{hor}$) identified as the strongest predictor of sprint ability ($r$ = 0.49-0.71). Finally, given the high shared variance between TH and QH variables, it is recommended that practitioners use only one of the tests in their assessment battery, the choice of which depends on the injury and athletic status of those being tested.

The focus of Section 4 was to translate the research findings of the thesis into applied resources for practitioners, using a “Masterclass” framework to bridge theory and practice. This synthesis provided physiotherapists and strength and conditioning coaches with practical guidance on implementing multiple hop assessments, monitoring asymmetries, and applying hop diagnostics to rehabilitation and performance enhancement.

This thesis presents original research that expands the understanding of how multiple hop testing can enhance diagnostic insights in athletic profiling. The findings demonstrate that simple, cost-effective technologies can be effectively integrated into assessments, providing valid and reliable measures of both athlete movement and outcome strategies. Although limitations included cross-sectional designs, male-dominated samples, and a focus on TH and QH tasks over other hop-based assessments, the research establishes a framework for incorporating hop assessments into applied practice. Future research should validate emerging technologies like AI-driven video analysis and inertial measurement units, broaden normative data across sexes and performance levels, and explore longitudinal and applied outcomes in clinical and elite sport environments.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF EQUATIONS

# COMMON ABBREVIATIONS

| | |
|---|---|
| ACL | Anterior cruciate ligament |
| ACLR | Anterior cruciate ligament reconstruction |
| CI | Confidence interval |
| CMJ | Countermovement Jump |
| CoM | Centre of mass |
| CoP | Centre of pressure |
| CV | Coefficient of variation |
| DOM | Dominant |
| DJ | Drop jump |
| ES | Effect size |
| fps | Frames per second |
| GRF | Ground reaction force |
| Hz | Hertz |
| ICC | Intra-class correlation coefficient |
| IMU | Inertial measurement unit |
| kg | Kilogram |
| LSI | Limb symmetry index |
| m | Metres |
| $m.s^{-1}$ | Metres per second |
| n | Number |
| N | Newtons |
| N.kg | Newtons per kilogram |
| Ns | Newton seconds |
| Ns.kg | Newton seconds per kilogram |
| NDOM | Non-dominant |
| p | Pixels |
| QH | Quintuple hop |
| SD | Standard deviation |
| *r* | Pearson correlation coefficient |
| RFD | Rate of force development |
| RSI | Reactive strength index |
| $RSI_{hor}$ | Horizontal reactive strength index |
| $RSI_{hor-DIST}$ | Horizontal reactive strength index (distance derived) |

| | |
|---|---|
| $RSI_{hor\text{-}FT}$ | Horizontal reactive strength index (flight time derived) |
| $RSI_{mod}$ | Reactive strength index modified |
| RTS | Return-to-sport |
| s | Seconds |
| SD | Standard deviation |
| SEM | Standard error in the mean |
| SJ | Squat jump |
| SSC | Stretch-shortening cycle |
| TEE | Typical error estimate |
| TH | Triple hop |
| V | Velocity |
| W | Watts |
| % Δ | Percentage change |
| 2-D | 2-Dimensional |
| 3-D | 3-Dimensional |

# ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except here explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

…………………………………………………………………….

Anthony Peter Sharp

20 September 2025

# PUBLICATIONS

## Thesis Publications

**Sharp, A.P.**, Cronin, J.B., & Neville, J. (2019). Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App. *Strength and Conditioning Journal, 41*(5), 96-107.

**Sharp, A.P.**, Neville, J., Diewald, S.N., Oranchuk, D.J., & Cronin, J.B. (2024). Videographic Variability of Triple and Quintuple Horizontal Hop Performance. *Journal of Sports Rehabilitation, 33*(7), 570-581.

**Sharp, A.P.**, Cronin, J.B., Neville, J., Diewald, S.N., Stolberg, M., Draper, N. & Walter, S. (2023). Comparison of Multiple Hop Test Kinematics Between Force Platforms and Video Footage: A Cross-sectional Study. *International Journal of Kinesiology and Sports Science, 11*(3), 23-28.

**Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple Hops? *Biomechanics, 5*(3), 67.

**Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen. *Applied Sciences, 15*(4), 1685.

**Sharp, A.P.**, Neville, J., & Cronin, J.B. (2025). Masterclass: Are You Getting the Most Out of Your Triple Hop Testing? *Physical Therapy in Sport, 76*, 111-119.

## Manuscripts Under Review

**Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Stretch-load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation. *Biomechanics (Under Review).*

**Sharp, A.P.**, Neville, J., & Cronin, J.B. (2025). Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design. *Strength and Conditioning Journal (Under Review).*

## Other Publications Relevant to this Thesis

Stolberg, M., **Sharp, A.P.**, Comtois, A.S., Lloyd, R.S., Oliver, J.L, & Cronin, J.B. (2016). Triple and Quintuple Hops: Utility, Reliability, Asymmetry and Relationship to Performance. *Strength and Conditioning Journal, 38*(3), 18-25.

# DECLARATION OF COLLABORATION

Chapters 2 to 9 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. My contribution and the contributions of various co-authors to each of these papers are outlined below. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

## STUDENT AND SUPERVISOR APPROVALS

***By signing you are confirming that the co-author contributions stated in the table(s) below are accurate.***

| | | | | | |
|---|---|---|---|---|---|
| **Student Name** | Anthony Peter Sharp | **Signature** | | **Date** | 20 Sep 2025 |
| **Supervisor Name** | John Barry Cronin | **Signature** | | **Date** | 20 Sep 2025 |

| | |
|---|---|
| **Chapter Number:** | **Chapter 2** |
| **Manuscript Title:** | Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App. |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Cronin, J.B., & Neville, J. (2019). Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App. *Strength and Conditioning Journal, 41*(5), 96-107. |
| **AUTHOR SURNAME** | **CONTRIBUTION** |
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **CRONIN** | Conception and design of the project or output; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **Chapter Number:** | **Chapter 3** |
| **Manuscript Title:** | Videographic Variability of Triple and Quintuple Horizontal Hop Performance. |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., Diewald, S.N., Oranchuk, D.J., & Cronin, J.B. (2024). Videographic Variability of Triple and Quintuple Horizontal Hop Performance. *Journal of Sports Rehabilitation, 33*(7), 570-581. |

| **AUTHOR SURNAME** | **CONTRIBUTION** |
|---|---|
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Analysis or interpretation of research data; |
| **DIEWALD** | Analysis or interpretation of research data; |
| **ORANCHUK** | Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **CRONIN** | Conception and design of the project or output; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **Chapter Number:** | **Chapter 4** |
| **Manuscript Title:** | Comparison of Multiple Hop Test Kinematics Between Force Platforms and Video Footage: A Cross-sectional Study. |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Cronin, J.B., Neville, J., Diewald, S.N., Stolberg, M., Draper, N. & Walter, S. (2023). Comparison of Multiple Hop Test Kinematics Between Force Platforms and Video Footage: A Cross-sectional Study. *International Journal of Kinesiology and Sports Science, 11*(3), 23-28. |

| **AUTHOR SURNAME** | **CONTRIBUTION** |
|---|---|
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Analysis or interpretation of research data; |
| **DIEWALD** | Analysis or interpretation of research data; |
| **DRAPER** | Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **WALTER** | Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **Chapter Number:** | **Chapter 5** |
| **Manuscript Title:** | Stretch-load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation. |
| **Publication Status:** | **Submitted for Publication** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Stretch-load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation. |
| **AUTHOR SURNAME** | **CONTRIBUTION** |
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; |
| **NAGAHARA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; |
| **WADA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; |
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **Chapter Number:** | **Chapter 6** |
| **Manuscript Title:** | Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple Hops? |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple Hops? *Biomechanics, 5*(3), 67. |
| **AUTHOR SURNAME** | **CONTRIBUTION** |
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; |
| **NAGAHARA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; |
| **WADA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; |
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

| | |
|---|---|
| **Chapter Number:** | **Chapter 7** |
| **Manuscript Title:** | Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen. |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen. *Applied Sciences, 15*(4), 1685. |
| **AUTHOR SURNAME** | **CONTRIBUTION** |
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; |

|  |  |
|---|---|
|  | Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; |
| **NAGAHARA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; |
| **WADA** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; |
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

|  |  |
|---|---|
| **Chapter Number:** | **Chapter 8** |
| **Manuscript Title:** | Masterclass: Are You Getting the Most Out of Your Triple Hop Testing? |
| **Publication Status:** | **Published** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., & Cronin, J.B. (2025). Masterclass: Are You Getting the Most Out of Your Triple Hop Testing? *Physical Therapy in Sport, 76*, 111-119. |
| **AUTHOR SURNAME** | **CONTRIBUTION** |
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; |
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

|  |  |
|---|---|
| **Chapter Number:** | **Chapter 9** |
| **Manuscript Title:** | Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design. |
| **Publication Status:** | **Submitted for Publication** |
| **Reference if published:** | **Sharp, A.P.**, Neville, J., & Cronin, J.B. (2025). Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design. |

| AUTHOR SURNAME | CONTRIBUTION |
|---|---|
| **SHARP** | Conception and design of the project or output; Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; Analysis or interpretation of research data; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |
| **NEVILLE** | Acquisition of research data where the acquisition has required significant intellectual judgement, planning, design, or input; Contribution of knowledge, where justified, including Indigenous knowledge; |
| **CRONIN** | Conception and design of the project or output; Contribution of knowledge, where justified, including Indigenous knowledge; Drafting significant parts of the research output or critically revising it so as to contribute to its quality and interpretation. |

# ACKNOWLEDGEMENTS

***"What is more noble than to grow old bringing wisdom to completion? For I am still learning, and I will not stop learning until I am done with life, and done with learning." - Seneca***

After nearly a decade and four career role changes, this PhD journey is finally reaching its destination, a life goal fulfilled. Along the way, so many people have supported me; sacrificing holidays, tolerating my divided attention, and generously giving their own time so I could chase this dream. To each of you, I extend my deepest and sincerest thanks.

*To Professor John Cronin….*

The man, the legend, JC. Thank you for your mentorship, guidance, and relentless belief in me. You've been there through the highs and the lows; when I was down, you either picked me up or gave me the kick I needed. What started as a mentorship has become a lifelong friendship. I may never fully repay you, but I am forever grateful.

Tumeke, JC!

*To Dr Jono Neville*

Thank you for stepping in as my Secondary Supervisor so early in your time at AUT. Your intelligence continues to blow me away, and I feel incredibly fortunate to have had your guidance on this PhD journey. I'll never forget our two weeks in Japan with Ryu and Tomo at National Institute of Fitness and Sport (NIFS), what an experience! From intense days of data collection to nights of Poki, craft beer roulette, random cuisine, and Mario Kart in Tokyo, we truly made the most of it. An unforgettable trip, and one that I'll always treasure.

*To Bryan Stronach….*

You were a constant source of support early in this journey. I am deeply grateful for the time you and NZC invested in me, as well as the financial support you provided. Your backing made a lasting difference, and I will always be thankful.

*To Professors Ryu Nagahara and Tomohito Wada….*

Japan, and especially Kanoya, will always hold a special place in my memory. Thank you so much for welcoming us into your family and for the generous time you gave. I am also deeply grateful to the faculty, students, and athletes at NIFS for the time and effort they dedicated to our studies; none of this research would have been possible without your incredible support and facilities.

*To AUT, the Faculty Leadership Team, and the Post-Graduate and Doctoral Students….*

This journey would not have been possible without the people around me. Thank you to AUT for your understanding and support through extensions and leave of absences. To my fellow students, I am grateful for the positive impact of our conversations, especially at writing retreats. Special thanks to Farhan, Dustin, Aaron, Chloe, Jamie, Kim, Joey and Frank, and of course to Shelley, whose support and dedication to numerous studies kept me on track throughout.

*To Renee, Jay and Millie….*

Thank you for your endless support and understanding over what feels like an eternity. It will be strange not to use my PhD as an excuse to avoid things anymore! Another big tick off the life bucket list and hopefully one that opens the door to more family adventures together.

*And lastly, to my future self….*

It was worth it, it took us to places we never thought we could reach, be proud of yourself.

# ETHICAL APPROVAL

Ethics approval for the relevant experimental work in this thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC) on 24 July 2017 for a period of three years, and by the National Institute of Fitness and Technology Ethics Board on 30 January 2018.

- AUTEC #17/133 – “Multiple hop testing – the diagnostic value to athlete profiling” for Chapters 3-7 (Appendix I)

- NIFS Kanoya Ethics Review Subcommittee document #8-123 – “Study on athlete profiling using single leg jump measures” for Chapters 3-7 (Appendix II)

## Acknowledgement of the Use of Generative AI Tools

During the preparation of this thesis, generative AI (ChatGPT) was used to assist with proofreading for grammatical purposes. All content generated through this tool was critically reviewed and revised to ensure accuracy and originality. No content was copied without substantial oversight and modification.

**THIS PAGE IS INTENTIONALLY LEFT BLANK**

# CHAPTER 1: INTRODUCTION

## 1.1 Background and Rationale for the Thesis

The reader should be aware that my PhD journey has been a lengthy one, starting in 2016. Therefore, the foundational literature for my approved PhD proposal and the sources that informed my early work should be read with this timeline in mind. In this regard, Chapter 1 presents my understanding of the literature at that time, which provided the background and rationale for the thesis. Implicit in this, and true to my original motivations for the PhD, is that the literature in this chapter has not been updated but reflects my thinking when I began the thesis, based on the knowledge available then. As you progress through the thesis, you will observe the integration of current research into the PhD narrative. With this in mind, Chapter 1 shows where the PhD started nine years ago.

Explosive propulsive movements such as those seen in sprinting (accelerations, maximum velocity, change of direction) are integral to success in sport, and athletic success relies on proficiency in these movements [9]. The level of proficiency has also been shown to clearly differentiate between various levels of competition [27]. It is generally thought that the mechanical factors influencing acceleration rely on concentric force production (horizontal orientation) [95, 111], net horizontal impulse [112] and activity of the knee and hip extensors [46]. Additionally, maximum speed appears to be dependent on a greater stretch-shortening cycle (SSC), lower limb stiffness, and hip extensor activity that generates maximum vertical ground reaction forces relative to body mass [27, 166, 167]. To attain high levels of these physical attributes, a certain level of training and monitoring should be employed to first gauge what levels of competency an athlete already possesses (profiling), and in designing and monitoring appropriate strength and conditioning programming to project an athlete to higher levels of athletic achievement.

Vittori (1995) highlighted several specific profiling assessments that were critical to sprint performance. These tests were organised into four categories: tests for acyclic expressions of strength; tests for cyclic expressions of strength; speed tests; and targeted running tests. As shown by these four assessment groups, monitoring and profiling should not focus solely on task-specific tests (such as sprint times) but should also measure the underlying qualities that contribute to success in that performance, especially when multiple physical characteristics are needed in an athletic skill. This provides important information for evaluating the effectiveness of individual training blocks and the physical traits being developed. Such information can then be used to predict whether an athlete is on track to reach their potential performance levels. Of particular interest and the focus of this thesis was the testing of cyclic expressions of strength and power.

A review of the assessment of ballistic performance [108] of the lower limb mostly favoured some form of bilateral vertical jumping. Although this appears to be common practice in the literature, very few athletic activities require the participant to propel themselves solely vertically and in a bilateral manner. Sporting demands more often involve multi-planar propulsion that includes vertical, horizontal, and lateral components simultaneously, such as diagonal changes of direction in response to an opponent’s actions. Additionally, these movements are cyclical rather than acyclical. Cyclic, unilateral, multi-axial propulsion seems to be important for optimal athletic performance, and researchers have suggested that horizontal jump performance is more likely a better predictor of performance in tasks like sprinting than vertical jumps [75]. Strength and conditioning practitioners should therefore incorporate some form of horizontal strength and power profiling into their practice to evaluate their importance in predicting performance and their potential link to injury risk, such as asymmetry.

Research focusing on the utility of unilateral horizontal propulsion assessments is prominent in the literature. Testing protocols include single-leg hops for distance [4, 84, 115, 132, 169], TH for distance [4, 84, 115, 132, 169], a 6 m hop for time [115, 132], crossover hop for distance [115, 132, 169], and more recently, lateral countermovement jump [109]. It should be noted that in many cases, these hops are used in clinical settings, especially in studies related to knee injury rehabilitation. Hopping ability in relation to performance among healthy athletes is rarely investigated. Single and TH tests for distance have both been used in testing batteries for athletic populations [105, 161].

The former test lacks cyclic, repeated, unilateral landing and subsequent propulsion, which are fundamental to the TH. This element seems to be very important in sports that require athletes to propel cyclically. The QH for distance is also used in training and assessment and is referred to as the 5-hop test in the literature [122]. Like its triple or 3-hop counterpart, this test involves cyclical, repeated, unilateral landings, followed by propulsion over longer distances and at higher speeds and intensities due to the momentum of the jumps. These tests are believed to more closely mimic movements found in sports requiring high levels of fast, explosive, and ballistic force [105, 162]. They may offer greater insight into athletic deficiencies by simulating the speed of contraction, neuromuscular firing patterns, and transfer of kinetic energy similar to those in sprinting and change-of-direction tasks [108]. The TH and QH in particular are thought to have repeated cyclical expressions of strength similar to sprinting and change-of-direction tasks [162]. For example, strong relationships ($r = -0.81$) have been noted between multiple hops and 40 m sprint performance [121]. Additionally, assessing the ratio of TH to QH is thought to demonstrate an athlete’s ability to sustain force application during faster movements, making it a key component of athletic performance. Vittori (1995) proposed that an athlete with a good capacity for rapid strength expression should perform at least 70% better on the QH compared to the TH test. The validity of this claim remains uncertain, and the limited research in this area motivated the pursuit of this body of work to thoroughly understand the diagnostic utility of the TH and QH for strength and conditioning coaches and physiotherapists.

## 1.2 Status of the Literature, Gaps and Limitations, and Rationale for the Thesis

This section provides a brief overview of the research that underpins the thesis and highlights the gaps and limitations that shaped the research questions of interest. As intimated previously, my PhD journey has been a lengthy one, beginning in 2016 and motivated by a literature review that I co-authored. The article was published in the Strength and Conditioning Journal in 2016 titled, "Triple and Quintuple Hops: Utility, Reliability, Asymmetry and Relationship to Performance." My contribution to the review was significant, considering the primary author was an undergraduate student interning with me at the time. However, because my contribution to the narrative review was less than 80%, the literature review cannot be included as part of the PhD, but it can be found in full in the appendices (Appendix III). Below is a summary of the main findings of the 2016 review and the gaps and limitations that led to some of the thesis questions.

Stolberg, Sharp et al. (2016) conducted a narrative review to assess the utility, reliability, normative data, asymmetry detection, and performance relevance of the TH and QH tests, both of which assess cyclic, unilateral, horizontal propulsion. The authors concluded that the TH for distance was a highly reliable measure, with intraclass correlation coefficients (ICCs) ranging from 0.80 to 0.98 and typical errors (SEM) usually below 20 cm. Although data on the QH was limited to a single study [122], initial results showed good reliability (ICC = 0.89), indicating its potential as a useful performance measure, though further validation was needed.

Regarding normative values, TH performance varied significantly among populations, with distances ranging from 4.28 to 6.90 m [23, 68, 69, 103, 104, 115, 132, 143]. Males consistently outperformed females, with differences in average hop distances of about 13.6% greater in some male populations. However, female-specific data was limited, restricting comparisons based on sex. Elite and highly trained individuals generally produced better hop distances compared to recreationally active participants.

The authors also identified that asymmetry in hop performance, measured by symmetry indices, generally ranged from 10 to 15% among healthy, recreationally active adults. Interestingly, QH seemed to highlight interlimb asymmetry more than TH, likely due to the longer hop sequence in the former and possible increased stretch-loading. Notably, the authors advised against relying only on group mean values when assessing asymmetry, as these can hide important individual differences.

When examining the relationship between hop performance and other athletic outcomes, moderate to very large correlations were identified between TH distance and short sprint performance ($r$ = -0.24 to -0.89), particularly in recreational and trained male populations [68, 103, 104]. Similarly, moderate to strong associations were found between TH and countermovement jump (CMJ) height [84, 113] and muscle torque output [69, 122, 143], although inconsistencies appeared across studies, partly due to differences in sample characteristics and testing procedures. In contrast, research on the QH’s link to performance measures was limited, with only one study reporting associations (r = 0.53 to 0.63) with CMJ forces and isokinetic strength [113].

Finally, the reviewers emphasised key methodological differences that influenced test outcomes and their interpretation. Variations in arm swing use, landing instructions, and limb dominance classification significantly affected performance, highlighting the need for greater standardisation in test protocols. The authors concluded that while the TH was found to be reliable and relevant for assessing athletic performance, the QH test remained underexplored and required further empirical investigation to fully assess its utility.

The following points summarise the gaps and limitations identified from the literature review, some of which formed the rationale for the thesis:

- Limited research on the QH. Despite its apparent usefulness in assessing cyclic unilateral propulsion, the QH has received minimal research attention. Only one study met the inclusion criteria for the review, which limits the ability to draw strong conclusions about its reliability, validity, and sensitivity. More empirical research across different populations is needed before the QH can be confidently recommended as a standardised performance test.
- Under-representation of female participants. Most studies included in the review focused on male or mixed-sex groups, with very few reporting sex-specific data. Only one study directly compared TH performance between males and females, highlighting a significant gap in understanding sex-related differences in test performance, variability, and asymmetry.
- Inconsistencies in testing protocols. Variability in how the TH and QH tests were administered across studies, such as in the use of arm swing, final landing instructions (bilateral vs. unilateral), and definitions of limb dominance, hindered cross-study comparisons and compromised the development of normative reference values.
- Over-reliance on distance as the sole outcome measure. Most studies evaluated performance solely based on hop distance, ignoring other potentially useful metrics such as ground contact time, and other kinematic and kinetic variables. Broadening measurement

methods and utilising advanced technology could improve the diagnostic and predictive power of these tests.

- Pooling heterogeneous samples in reliability analyses can be problematic. Some studies combined male and female data or merged recreational and elite athletes, which may have artificially boosted reliability metrics like ICCs. This hampers the interpretation and generalisation of the results and highlights the importance of stratified analyses by sex, training status, and competitive level. Additionally, measures of typical error (CV, SEM) related to the QH are necessary to fully understand the reliability of this protocol.
- Using group means to report asymmetry can hide important individual differences. Asymmetry was often presented with averages and standard deviations, which can mask individual variations. Because asymmetry may be crucial for monitoring performance and injury risk, future researchers should prioritise analyses and reporting methods that emphasise fluctuations within individuals.
- Lack of longitudinal and predictive research designs. The reviewed studies were primarily cross-sectional, providing limited insights into the test–retest reliability or the predictive value of hop performance for injury risk or athletic progression. Longitudinal studies that track changes in hop test performance over time and examine its relationship to performance and injury outcomes are essential to determine the true practical utility of these tests.
- Limited research links QH to other performance markers. Although the TH test has been studied in relation to sprinting, vertical jumping, and strength measures, the QH has not been examined similarly. Its links with key performance indicators are mostly unknown, limiting its current usefulness for practitioners seeking comprehensive athlete profiling tools. Working with athletes or sports teams often requires real-time feedback to assess current athlete status and readiness, the transfer of physical training to sporting

performance, and measures of neuromuscular fatigue. Therefore, it is important to quantify the many outcome and movement strategy variables related to multiple hop-based performance in the field.

## 1.3 Overarching Question and Sub-questions

Based on the brief treatise of the literature and the identified gaps and limitations, the thesis aimed to address the overarching question, “Can technology integration into multiple hop testing provide greater diagnostic insight to better inform physiotherapeutic and strength and conditioning practices?” To answer this question, several specific research questions were developed.

- What is the current status of the research on TH and QH regarding utility, reliability, asymmetry, and their relationship to performance (Appendix III)?
- Can smartphone videos offer a valid and reliable way to assess multiple hop variables?
- What are the physical demands of the TH versus QH?
- Do outcome and movement strategy variable asymmetries differ within and between hops?
- Is the performance of multiple hops in series closely related to sprint performance?
- How can the findings uncovered throughout the thesis be translated into a resource that enhances understanding of the usefulness of multiple hop assessments to improve strength, conditioning, and physiotherapy practices?

## 1.4 Significance of the Thesis

In the first instance, there was surprisingly little information available on multiple hop assessment variables besides total distance jumped, and clarifying and expanding the knowledge in this area could benefit profiling, monitoring, and training design once reliability is established. However, the main goal of this thesis was to provide a comprehensive overview of how to implement multiple hop assessments to improve evaluation and exercise prescription. It does so by utilising technology to measure kinematic and kinetic qualities that are often overlooked when focusing only on distance. This technological approach allows for a more thorough evaluation of the usefulness of multiple hop assessment, which should be valuable for strength and conditioning coaches, physiotherapists, athletes, and researchers seeking better clinical and athletic outcomes. To support these efforts, resources on multiple hop assessments were created for physiotherapy and strength and conditioning practice, aiming to: 1) enhance understanding of the biomechanics behind TH and QH; 2) explore the key factors influencing these jumps and how these variables can inform better diagnostics and training; and 3) show how different technologies can measure various elements within the deterministic model. By translating the thesis findings into practical educational materials, it is hoped that this work will make a meaningful contribution to physiotherapy and strength and conditioning practices.

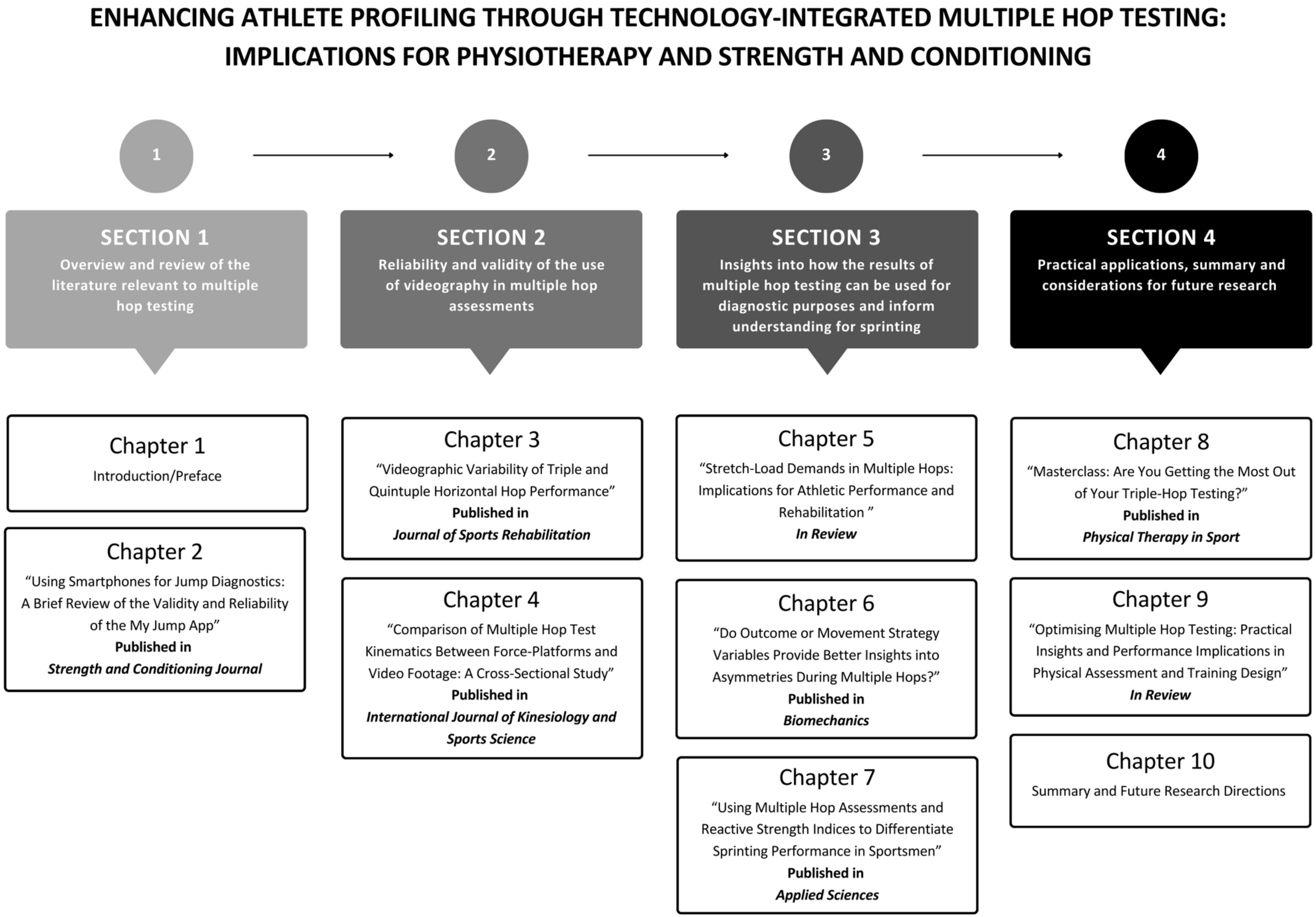
## 1.5 Structure of the Thesis

The chapters in this thesis are formatted for publication in peer-reviewed journals (see Publications section). Therefore, each chapter is written to be understood independently from the others. Due to this thesis-by-publication approach (i.e., a Pathway 2 Thesis), there may be some repetition both between chapters and throughout the thesis. To help create a cohesive narrative, preludes have been added at the start of each chapter to explain how each one connects to the previous, helping the reader understand the flow of ideas and the overall cohesiveness of the thesis. The content of this work is divided into 10 chapters across four distinct sections (see Figure 1).

- Section one includes Chapters 1 and 2: Chapter 1 provides a brief review of the existing literature on multiple hops, focusing on utility, reliability, and asymmetry. It identifies gaps and limitations that justified the thesis direction. This section details the research questions, explains the significance of the thesis, and outlines the structure. A key conclusion from the literature review was the need to measure multiple hop performance with methods beyond just distance. This insight shifted the focus of Chapter 2, which examined literature on the accuracy and sensitivity of smartphone video, along with the reliability and validity of jump diagnostics.

- Section two includes two chapters focusing on the reliability and validity of using videography in TH and QH assessments. Specifically, in Chapter 3, a tablet and free software (Kinovea) were used to assess the between-rater, within-rater, and test-retest variability of temporal events related to multiple horizontal hop testing. In Chapter 4, multiple hop kinematics captured via smartphone videography and processed with Kinovea were compared to gold standard in-ground force plate (x 54 technology).
- Section three includes three chapters that provide insights into how the results of multiple hop testing can be used for diagnostic purposes and to enhance understanding of sprinting. Specifically, the aim of Chapter 5 was to better understand and quantify the kinetic demands of multiple hops in series, with a focus on determining the increased demands of a QH task compared to the more common TH task, the stretch-load demands of particular interest. In Chapter 6, the utility of TH and QH kinematics and kinetics for describing vertical and horizontal cyclic asymmetries was examined. Chapter 7 focused on the relationship between hop and sprint performance, specifically whether different kinematic and kinetic measures and their ratios could differentiate between sprinters of varying skill levels.
- Section four comprised three chapters that compiled the gathered information into practical applications and future research directions for various practitioners. Chapter 8 synthesised the findings from the thesis and places them in a context aimed at improving physiotherapeutic practice by expanding the understanding of what multiple hop diagnostics could provide with

technology integration. Chapter 9 follows a similar approach but focuses on synthesising previous findings into a context more specific to strength and conditioning coaches. Finally, Chapter 10 provides a summary of the main findings and outlines future research directions.



**ENHANCING ATHLETE PROFILING THROUGH TECHNOLOGY-INTEGRATED MULTIPLE HOP TESTING: IMPLICATIONS FOR PHYSIOTHERAPY AND STRENGTH AND CONDITIONING**

1 → 2 → 3 → 4

**SECTION 1**
**Overview and review of the literature relevant to multiple hop testing**

Chapter 1
Introduction/Preface

Chapter 2
"Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App"
**Published in**
***Strength and Conditioning Journal***

**SECTION 2**
**Reliability and validity of the use of videography in multiple hop assessments**

Chapter 3
"Videographic Variability of Triple and Quintuple Horizontal Hop Performance"
**Published in**
***Journal of Sports Rehabilitation***

Chapter 4
"Comparison of Multiple Hop Test Kinematics Between Force-Platforms and Video Footage: A Cross-Sectional Study"
**Published in**
***International Journal of Kinesiology and Sports Science***

**SECTION 3**
**Insights into how the results of multiple hop testing can be used for diagnostic purposes and inform understanding for sprinting**

Chapter 5
"Stretch-Load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation "
***In Review***

Chapter 6
"Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple Hops?"
**Published in**
***Biomechanics***

Chapter 7
"Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen"
**Published in**
***Applied Sciences***

**SECTION 4**
**Practical applications, summary and considerations for future research**

Chapter 8
"Masterclass: Are You Getting the Most Out of Your Triple-Hop Testing?"
**Published in**
***Physical Therapy in Sport***

Chapter 9
"Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design"
***In Review***

Chapter 10
Summary and Future Research Directions

**Figure 1.** Thesis framework

# CHAPTER 2: USING SMARTPHONES FOR JUMP DIAGNOSTICS: A BRIEF REVIEW OF THE VALIDITY AND RELIABILITY OF THE MY JUMP APP

This chapter comprises the following paper published in the Strength and Conditioning Journal.

**Reference:**

Sharp, A.P., Cronin, J.B., & Neville, J. (2019). Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App. Strength and Conditioning Journal, 41(5), 96-107.

## 2.0 Prelude

One of the main findings and concluding statements from Chapter 1 was that researchers were primarily focused on reporting total distance only, and that “the quantification of the TH test by means other than simply through distance measures may improve the utility of the test.” Capturing and analysing such information is usually expensive and laboratory-based. However, advances in commercial smartphone technology have increased their use in sports performance and medical settings for biomechanical analysis. Still, the accuracy and sensitivity of this technology for monitoring jump/hop performance are largely unknown. Therefore, this review of the literature aimed to assess the accuracy, sensitivity, reliability, and validity of smartphone video, as well as its potential usefulness in improving jump/hop diagnostics.

## 2.1 Introduction

The use of various bilateral and unilateral jump or hop-based tests are common in athletic profiling as they resemble ballistic movements from sports performance such as jumping and sprinting. The proficiency of these movements is paramount for athletic success [9] and have strong correlations as such with tasks including sprint performance [5, 15, 68, 75, 83, 162] and multi-directional speed [98]. Vertical and horizontal-based tests invariably only require the use of a tape measure to record jump distance or height achieved during each trial, or a basic contact mat to measure flight time. However, the potential to capture the kinematic and kinetic characteristics of each trial and describe how an athlete achieves their jump performance, which in the simplest of terms is defined by distance or height achieved, could also be of significant value in determining athletic potential. Capture of such information usually requires the use of expensive laboratory-based equipment such as force platforms [160], motion capture systems [160], pressure sensors [33], or photocell technology (Optogate™) [101], as well as a high level of training to analyse the output data.

The use of 3-dimensional (3-D) video motion analysis is the gold standard for use in assessing the quality of jumping and landing tasks. However, the use of low-cost two-dimensional (2-D) smartphone or tablet video technology integrated with low-cost biomechanical analysis applications could provide valid and reliable access to high levels of data captured outside of a laboratory environment [10, 14, 70, 72] and a more affordable and more readily available solution. The current market is flooded with applications such as Jumpster, myVertical and Vertical Jump Calculator that utilise the inbuilt accelerometers and gyroscopes within a smartphone. Recent technological advancements in mobile phone video technology, and specifically the availability of high frame rates and screen resolutions in smartphones, has resulted in an exponential increase in their use in sports performance, health, wellness, and in medical cohorts. Applications such as

What’s My Vertical, My Jump and its later release My Jump 2 utilise this video technology to derive various jump diagnostics in several different assessments. This brief review of the literature will determine the accuracy of smartphone video, the reliability and validity of these variables in jump diagnostics and will provide some practical insight, cautions and recommendations for its use in jump diagnostics for the strength and conditioning practitioner.

### 2.1.1 My Jump Smartphone Application

A review of the literature showed a distinct lack of studies in this area, and as such only six studies were included for review (Table 1). All six studies pertained to a proprietary smartphone application called My Jump and its later upgraded release My Jump 2 which has the capability to assess several jump-based tests; vertically orientated jumps (CMJ, squat jump - SJ, drop jump - DJ) and horizontally orientated jumps (standing long jump), as well as a function for force-velocity profiling and tests for asymmetry (Figure 2).

**Table 1.** Studies investigating the accuracy, reliability and validity of smartphone video for jump diagnostics

| Author | Profile (sex, age ± SD, body mass, height) | Objective/Technology | Variables | Validity | Reliability |
|---|---|---|---|---|---|
| Balsalobre-Fernández et al. [10] | n = 20 male recreational active students, age 22.1 ± 3.6 years, body mass 74 ± 10.4 kg, height 1.81 ± 0.8m. | To determine the concurrent validity and reliability of an iPhone 5s application (My Jump) integrated high-speed camera (120 fps, 720 p) for measuring vertical jump performance. | CMJ<br>*(jump height)* | Against force platform 1000 Hz<br>$r$ = 0.995 | **Within (intra) session (subject):**<br>Tester 1: α = 0.997, CV = 3.4%;<br>Tester 2: α = 0.988, CV = 3.6%<br>**Within (intra) session (device):**<br>ICC = 0.997<br>**Between tester (inter-rater):**<br>ICC = 0.999 |
| Carlos-Vivas et al. [31] | n = 40 active students; 29 male, 11 female, age 21.4 ± 1.9 years, body mass 68.7 ± 8.4 kg, height 1.74 ± 0.07 m. | To determine the validity of iPhone 6 application (My Jump) with integrated high-speed camera (240 fps, 720 p) for measuring vertical jump performance. | CMJ<br>*(jump height)* | Against force platform at 1202 Hz<br>My Jump / Time in air method ICC = 1.000, α = 1.00<br>My Jump / Velocity at take-off method ICC = 0.996, α = 0.996 | **Within (intra) session (device):**<br>ICC = 0.983 |
| Driller et al. [51] | n = 61 various athletic ability (active-high trained); 30 male, 31 female, age 20 ± 4 years, body mass 76.4 ± 15.2 kg. | To determine the concurrent validity and reliability of iPhone 6s application (My Jump) integrated high-speed camera (240 fps, 720 p) for measuring vertical jump performance. | CMJ<br>*(jump height, flight time)* | Against force platform at 200 Hz<br>Jump height $r$ = 0.96 (0.96 – 0.97), mean bias 0.9 ± 0.2 cm, TEE = 9.7 %<br>Flight time $r$ = 0.96 (0.95 – 0.97), mean bias = 8 ± 5 ms, TEE = 19 ms | **Between tester (inter-rater):**<br>Jump height: CV = 5.8%, TEE = 1.4 cm, ICC = 0.97 |
| Gallardo-Fuentes et al. [61] | n = 21; 14 male track and field athletes, 7 female track and field athletes, age 22.1 ± 3.6 years, body mass 74 ± 10.4 kg, height 1.81 ± 0.8m. | To determine inter and intra-session reliability and validity of an iPhone 6 application (My Jump) integrated high-speed camera (240 fps, 720 p) for measuring various jump actions in trained male and female athletes. | 40-cm DJ<br>*(jump height)*<br>CMJ<br>*(jump height)*<br>SJ<br>*(jump height)* | Against contact mat<br>40-DJ male $r$ = 0.99<br>40-DJ female $r$ = 0.97 - 0.98<br>CMJ male $r$ = 0.99<br>CMJ female $r$ = 0.97 - 0.98<br>SJ male $r$ = 0.99<br>SJ female $r$ = 0.96 - 0.98 | **Within (intra) session (subject):**<br>40-DJ male α = 0.96, CV = 6.05 – 6.57 %<br>40-DJ female α = 0.94, CV = 5.20 – 6.06 %<br>CMJ male α = 0.99, CV = 4.38 – 4.64 %<br>CMJ female α = 0.99, CV = 4.59 – 7.60 %<br>SJ male α = 0.97, CV = 5.35 – 5.63 %<br>SJ male α = 0.98, CV = 3.77 – 5.48%<br>**Within (intra) session (device):**<br>40-DJ male ICC = 0.99, female ICC = 0.98 – 0.99<br>CMJ male ICC = 0.99, female ICC = 0.98 |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | SJ male ICC = 0.98– 0.99, female ICC = 0.97 – 0.98<br>**Between (inter) session:**<br>40-DJ male $r$ = 0.84, female $r$ = 0.76<br>CMJ male $r$ = 0.93, female $r$ = 0.86<br>SJ male $r$ = 0.82, female $r$ = 0.93 |
| Haynes et al. [72] | n = 14 male sports-science students, age 29.5 ± 9.9 years, body mass 81.4 ± 14.1 kg, height 1.78 ± 0.1 m. | To determine the validity and reliability of an iPhone 6 application (MyJump-2) with integrated high-speed camera (240 fps, 720 p) for measuring reactive-strength (RSI) and drop-jump performance. | 20-cm DJ<br>*(RSI, jump height, contact time, mean power)*<br>40-cm DJ<br>*(RSI, jump height, contact time, mean power)* | Against force platform at 1200 Hz<br>20-DJ RSI $r$ = 0.938; jump height $r$ = 0.812; contact time $r$ = 0.963; mean power $r$ = 0.655<br>40-DJ RSI $r$ = 0.969; jump height $r$ = 0.959; contact time $r$ = 0.981; mean power $r$ = 0.571 | **Within (intra) session (subject):**<br>20-DJ RSI α = 0.98, CV = 6.71%<br>40-DJ RSI α = 0.99, CV = 10.32%<br>**Within (intra) session (device):**<br>20-DJ RSI ICC = 0.954, jump height ICC = 0.803, contact time ICC = 0.986, mean power ICC = 0.507<br>40-DJ: RSI ICC = 0.983, jump height ICC = 0.958, contact time ICC = 0.920, mean power ICC = 0.568 |
| Stanton et al. [154] | n = 29 recreationally active; 10 male, 19 female, age 26.41 ± 5.36 years, body mass 72.62 ± 12.91 kg, height 1.72 ± 0.78 m. | To determine concurrent validity and intra-rater reliability of an iPhone 6s application (My Jump) with integrated high-speed camera (240 fps, 720 p) against force platform measurements. | 30-cm DJ<br>*(jump height)*<br>CMJ<br>*(jump height)* | Against force platform at 1000 Hz<br>30-DJ $r$ = 0.999<br>CMJ $r$ = 0.998 | **Within tester (intra-rater):**<br>30-DJ ICC = 0.99<br>CMJ ICC = 0.99<br>**Within (intra) session (device):**<br>30-DJ ICC = 0.99<br>CMJ ICC = 0.99 |

**Key:** ICC = intraclass correlation coefficient; CV = coefficient of variation; TEE = typical error estimate

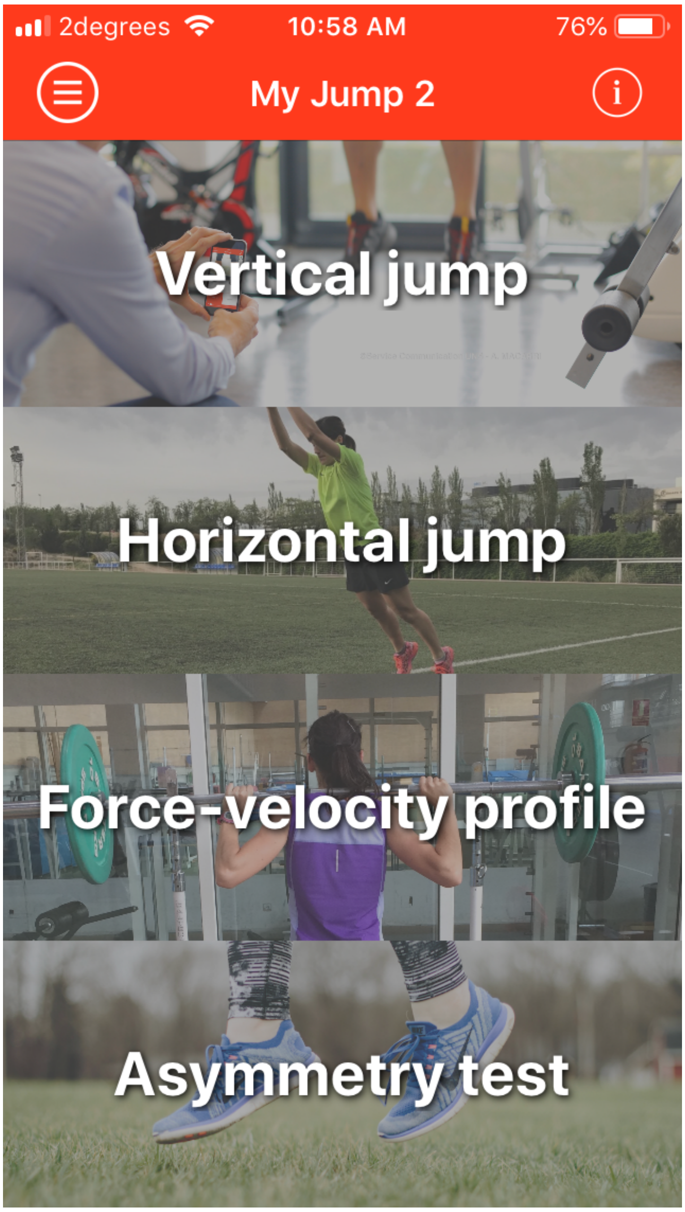
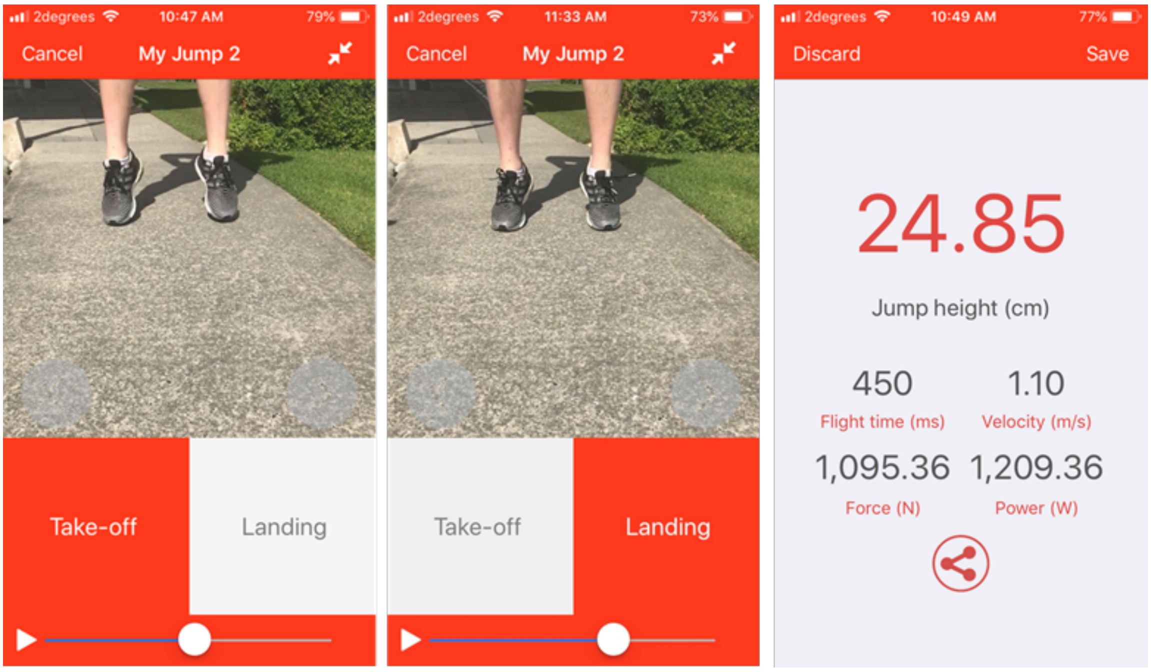


**Figure 2.** The My Jump 2 application interface

Each of the tests provide several output variables depending on the test relating to athletic performance, including jump height (cm), flight time (ms), velocity (m.s$^{-1}$), force (N), power (W), reactive strength index (RSI). The integrated high-speed camera in the iPhone is used to capture each jump, and frames are used to compute time and all subsequent variables by using predetermined leg length and the subject's mass. Total flight time is measured by manually selecting the first video frame where the subject loses contact with the ground (take-off), and a second frame when the subject regains contact with the ground (point of landing) (Figure 3). The integrated high-speed camera technology in the smartphone for each of the studies reviewed was dependent on the model, varying from 120 frames per second (fps) 720p in the iPhone 5s, to 240fps 720p in the iPhone 6s.



24.85
Jump height (cm)

450
Flight time (ms)

1.10
Velocity (m/s)

1,095.36
Force (N)

1,209.36
Power (W)

**Figure 3**. Screenshot of My Jump 2 CMJ assessment and variable output

### 2.1.2 Determining Validity and Reliability of the Practical Measure

It is important that the strength and conditioning practitioner has established the levels of both reliability and concurrent validity for a technology or device (practical measure) before deciding whether to use it in their practice. Concurrent validity reflects the ability of a practical measurement tool to accurately detect what it is designed to measure [7] when compared to a criterion value, which is normally measured using a 'gold-standard' device. In this case the practical measure being jump height, flight time, contact time, mean power and RSI from the My Jump application on the iPhone, and those from criterion measures, which in this case were measured using a force platform [10, 31, 51, 61, 72] or contact mat [154].

When comparing both practical and criterion measures for validity, both qualitative (scatterplots) and quantitative (linear regression) assessments provide a useful understanding of the relationship between the two sets of data [77]. Use of a linear regression will determine any fixed or proportional bias in the practical measure but would assume that there is no error in the measurement of the criterion. Where there is a possibility of error in the measurement of the criterion, but both sets of data are measured in the same units, the use of Bland-Altman plots could be more suitable than a regression analysis.

Measures of reliability determine the consistency of a test measurement and its reproducibility [164] on multiple occasions, an extremely important criterion when profiling athletes and monitoring performance over time. For a comprehensive understanding of consistency, measures of both absolute and relative reliability should be determined [7].

Absolute consistency refers to the stability of measures and the typical variation within individuals and is determined using the coefficient of variation (CV), which is typically reported as a percentage of the mean, SEM, or as Cronbach's α coefficient (a measure of internal consistency). It is generally accepted that a CV of less than 10% shows a good level of agreement [7]. A Cronbach's α coefficient level of ≥ 0.7 or < 0.9 is generally accepted as good, and an α level ≥ 0.9 is accepted as excellent [126].

Relative consistency refers to the reproducibility of rank order or position between methods or over time and is determined using ICCs, or less favourably a Pearson correlation coefficient (r), the latter being a measure of correlation and not agreement. A measure of reliability should reflect both correlation and agreement and ICCs are an appropriate method for determining this [87]. Koo and Li [87] suggest the magnitude of a correlation coefficient is as follows; < 0.5 are indicative of poor reliability, values ≥ 0.5 and < 0.75 indicate moderate reliability, values between ≥ 0.75 and < 0.9 indicate good reliability, and values ≥ 0.90 indicate excellent reliability.

Each measure of consistency has a degree of error which needs to be understood when interpreting the data so that the practitioner can understand what changes are meaningful. This degree of error can be due to either biological error (subject-related factors), technological error (apparatus) or tester error, and are either systematic (due to fatigue or a learning effect) or random chance (biological variability, alertness). They are evident as either a constant (affects all scores equally) or as a bias (only affects certain scores) [164] in which case a log transformation is required before analysis [77].

Of the six studies in this review all reported measures of absolute consistency using CVs (five studies), Cronbach's α coefficient (five studies), and Bland-Altman plots (six studies). Measures of relative consistency were reported using ICCs (six studies) and Pearson correlation coefficients (two studies). The application of these statistics differed between studies depending on the study approach; within-session, between-session and between-tester.

### 2.1.3 Jump Height

Jump height is the most widely used and practical variable used to assess an athlete's ability to produce force rapidly [108], and its context is dependent on the test used, whether it is from a static position (SJ) utilising a slow stretch shortening cycle (CMJ) or a rapid stretch shortening cycle (DJ). Jump height is calculated by My Jump from flight time using Equation 1 from Bosco et al. [24] where $h$ is the total displacement of the centre of gravity in meters (height jumped); $t$ is total flight time in seconds; $g$ is the acceleration due to gravity (9.81 $m.s^{-2}$).

$$Jump\ Height\ (h) = \ t2\ \times 1.22625 \text{ or } \frac{\mathrm{g} \cdot \mathrm{t2}}{8}$$

**Equation 1.** Jump height calculation using flight time

The criterion method for assessing jump height is a force platform and can be derived using either the flight time method [10, 31, 51, 61, 72, 154] or by calculating jump height using the velocity at take-off on the force platform [31] as described by Ferragut et al. [56] in Equation 2, where *h* is the total displacement of centre of gravity in meters (height jumped); *Vd* is the model of vertical velocity at take-off in meters per second; *g* is the acceleration due to gravity (9.81 m.s$^{-2}$).

$$Jump\ Height\ (h) = \frac{Vd2}{2g}$$

**Equation 2.** Jump height calculation using take-off velocity

Five studies have investigated the concurrent validity of CMJ height with either force platforms [10, 31, 51, 154] or with a contact mat [61]. All five studies used the flight time method [24] for the calculation of jump height and supported the concurrent validity of CMJ height with criterion values (*r* = 0.96 - 0.995; force platform, *r* = 0.97 - 0.99; contact mat). One study [31] also investigated the concurrent validity of CMJ heights from both the flight time method and the velocity at take-off method [56] using a force platform, showing a perfect correlation with total flight time (ICC = 1.00) and a very high correlation with velocity at take-off (ICC = 0.996). The researchers did however show a systematic bias between the My Jump and force plate measures, and an overestimation of jump height from the application of 0.78% when compared to the velocity at take-off method. One possible explanation they had for this was the differences in sampling frequency between the smartphone video (240 Hz) and the force platform (1202 Hz). This study also showed no substantial differences for concurrent validity between male and female cohorts performing CMJ [61].

CMJ height of males (CV = 3.4 – 4.64 %) however shows more within-session absolute consistency than their female counterparts (CV = 4.59 - 7.60 %) at both 120 fps and 240 fps using the My Jump application [10, 61]. This greater variability within females might be a function of the group size (only 7 of the 41 subjects) and the athletic profile variation (3 sprinters, 3 long distance runners, 1 thrower), but that contention would need further investigation. Greater variability was seen with DJ (CV = 5.20 – 10.32 %), the highest variability related to the height of the drop (40 cm) and training background of the subjects, i.e. sport science students [72]. Given the greater technical and physical demands associated with the drop jump, the increase in variability is likely a reflection of biological variability rather than technological.

Both male and female jump heights showed excellent levels of internal consistency (α = 0.94 - 0.997) during CMJ [10, 61], SJ [61] and 40 cm DJ [61]. Within-session relative (rank order) consistency of the My Jump application has also shown to be excellent (ICC = 0.97 – 0.997; force platform, ICC = 0.983 - 0.997; contact mat, ICC = 0.98 - 0.99) for CMJ heights between My Jump and force platform [10, 31, 51, 154] and contact mat [61], and with no substantial differences observed between male and female cohorts [61]. There were also similar findings for SJ (ICC = 0.97 – 0.99), 30 cm DJ (ICC = 0.99), 40 cm DJ (ICC = 0.958 – 0.99), and good relative consistency for 20 cm DJ (ICC = 0.803) [61, 72].

It is important for practitioners to ensure rater consistency when selecting the correct frames in detection of jump heights across multiple sessions when following the protocol for the My Jump application. A single study [154] has investigated the intra-rater reliability of determining jump height and reported near perfect agreement in rank order consistency (ICC = 0.99) of 116 video trials for both 30 cm DJ and CMJ seven days apart. However, it should be noted that measures of jump height on day one were consistently higher than those measured again on day 8 for both the CMJ and DJ. Further analysis showed that these mean differences were only 0.38 to 0.43 cm for both tests, an error most likely caused by identifying a single video frame difference for either the take-off and/or landing.

Inter-rater reliability refers to the ability of two or more raters to quantify a measure accurately and is especially important when there are some subjective aspects to the assessment procedure. In the case of the My Jump and My Jump 2 application, the point of take-off and landing must be manually selected, and hence it is important to determine the variability if different users were to use the technology. Only one study [51] has reported absolute inter-rater reliability (CV = 5.8%) using smartphone technology. Only two raters/researchers were used in this study to rate 50 jumps, and it would be interesting to note the magnitude of variability (CV) if more raters were used and/or raters that did not have a sport science/research background. Inter-rater reliability needs to reflect the variation associated with end users of the technology, and as such, a broader cohort of raters indicative of potential end users is recommended.

Balsalobre-Fernandez et al. [10] reported excellent levels of relative inter-rater reliability (ICC = 0.99) indicating almost perfect agreement between two raters. Of note was that both raters were completely independent of the study design and as such were likely less skilled in the use of the My Jump application compared to the researchers, reporting on average only a difference of approximately 1 mm. Driller et al. [51] also found small differences between raters assessing the same video footage (TEE = 1.4 cm). It would seem from the results in this section that the smartphone video technology can be used reliably by multiple users to determine jump height.

A major limitation in the methodological approaches taken by the authors is the absence of any time series reliability over repeated testing occasions. Only one research group determined relative stability over two testing occasions [61], reporting high positive to very high positive correlations (*r* = 0.76 – 0.93) between measures on two separate testing sessions 48 hours apart for jump height in CMJ, SJ and 40cm DJ in a mixed sex group. The researchers took care to reduce any biological error by testing at the same time of day, wearing of the same sports clothing, jumping on the same surface, and tested by the same researchers. Subjects were also instructed to refrain from any hard physical training between sessions, however due to the background of the subjects (high-level track and field athletes), abstinence from training was highly unlikely, and the absence of a third testing day meant that determination of any trends pertaining to systematic error was not clear. Also of interest was the use of a Pearson correlation coefficient rather than an ICC. The former statistic overestimates the true correlation for small sample sizes (less than ~ 15), whereas the ICC does not have this bias with small samples [76]. There is no doubt that further investigation with appropriate statistical methods is needed to elucidate the relative test-retest reliability of measures used by smartphone video in the assessment of jump performance.

### 2.1.4 Power

Power relates to the ability of an athlete to produce force rapidly [106]. Only moderate correlations have been observed (*r* = 0.571 - 0.655) for mean power derived using the My Jump application compared to a criterion values measured directly from force platforms during both 20 cm and 40 cm DJ assessments [72]. This is not unexpected given the error in calculating mean power from jump height rather than the direct measurement of force from a platform [71]. The same study also showed moderate within-session relative consistency (ICC = 0.507 - 0.568) for mean power during DJ performance. In this study mean power was calculated from body mass, jump height and vertical push-off distance (a predetermined distance measured using an assumed countermovement depth) [135]. The variability in mean power derived from direct measures on the force platform versus computed measures indirectly from the My Jump application must be due to variations in jump strategy or inaccurate measures of effective mass. Subject mass does not change between trials, and flight time has been shown to be extremely reliable, so variability in vertical push-off distance and effective mass, both due to jump strategy, must be affecting the mean power outputs. Caution should therefore be taken when reporting mean power during drop jump performance using the My Jump application.

### 2.1.5 Reactive Strength

RSI explains the capacity for an athlete to produce maximal concentric force immediately preceded by a rapid eccentric action in minimal time, and is often described using the ratio between height jumped and the contact time during drop jumps [106]. DJ variations provide a practitioner to assess these qualities due to their nature of a rapid eccentric load during landing immediately followed by an explosive concentric jump. Both contact time and subsequent flight time can then be measured.

Very high positive correlations ($r$ = 0.96 – 0.98) have been seen in ground contact times for 20 cm and 40 cm DJ using My Jump and force platforms [72], and for the derived RSI ($r$ = 0.938 – 0.969) [72]. Excellent within-session reliability in RSI (ICC = 0.954 – 0.983) and contact time (ICC = 0.920 - 0.986) was also seen [72]. You could assume similar levels of validity and reliability for contact time and RSI for 30 cm DJ, although this was not determined [154]. This purports to the fact that faster SSC movements such as DJ measuring contact times and RSI, as well as slower SSC movements can be accurately measured using the My Jump application. This is understandable as they are both derived from time-based measures.

## 2.2 Discussion

The purpose of this brief review was to determine the level of reliability and validity of certain measures of jump performance using smartphone video technology and specifically the practical applications and limitations of a proprietary application called My Jump. The availability of high-speed video technology such as that found in smartphones, with integrated applications such as My Jump have made the measurement of vertical jumps easier to perform and provides an extremely practical way of assessing and monitoring athlete performance in the field.

A total of 185 subjects (63% - 117 male; 37% - 68 female) were included in the six studies under review, with an average age of 22.5 ± 5.4 years, body mass 74 ± 13 kg and height 1.76 ± 0.6 m. Five of the six studies included subjects who were described as 'recreationally active' for the most part, with only a single study describing athletes of a sub-elite to elite nature (n = 21; 14 male, 7 female) [61]. It could be assumed that those subjects who were not highly trained (88.6 % of subjects) did not regularly perform jump training and therefore their movement proficiency in such tests could be questionable. Consequently, there is a greater potential for within-session biological variation and between-session systematic error due to possible familiarisation, fatigue, the effect of learning, anatomical variations, time of the day, and the subject's level of training.

All six studies reviewed measured performance in vertically orientated jumps, although the most recent release of My Jump now includes bilateral horizontal jump measurement of distance there is currently nothing in the literature to support its level of validity or reliability. Further developments in the use of smartphone video technology could provide insight into horizontally orientated unilateral assessment of reactive strength such as multiple hops in series. Such assessments would require determination of both reliability and validity at greater distances than those reviewed in current studies (approximately 1-2 m distance from the device) to determine the accuracy and consistency of measures of ground contact and flight time.

### 2.2.1 Improvements in Smartphone Video Technology

With the improvements and evolution of smartphone video technology in the commercial marketplace the resulting question is; does higher frame rate and resolution improve levels of reliability or validity in jump variables? Balsalobre et al. [10] suggested that a smartphone such as the iPhone 5s, which captured video at only 120 fps, may miss either the take-off or landing frame, and that longer flight time errors in measurement would be exacerbated due to the equation for jump height being flight time squared. They suggested that improvements in future technology might mean improved validity, however no significant differences have been seen in either validity or reliability since the release of the iPhones 6 and 6s which record at 240 fps and 720 p and levels of agreement remain high [61]. Further improvements in resolution to 1080 p since the release of iPhone 7 in September 2016, to the most recent release of the iPhone X could further increase detection of key timing events and reduce some of the bias evident. The release of My Jump on Android has also increased further potential with devices such as the Sony Xperia with capability to capture slow-motion video in 1080p at 960 fps, and advancements in gesture and movement recognition software in smartphones may provide even further uses of these practical devices in a field-based setting.

### 2.2.2 Limitations

It seems that smartphone video technology with an integrated biomechanical assessment application shows a promising level of reliability and validity across a range of jump tests and populations. Table 2 highlights the practical uses of various jump assessments, smartphone specifications, jump variables and their associated levels of validity and reliability, along with several methodological limitations or precautions for their use. The primary limitation of concern is an absence of authors reporting test-retest reliability of this technology as the use of within-session reliability is of limited value, and understanding the variability associated with using the technology over multiple testing sessions would seem more important. Further research is therefore needed to determine the stability of the smartphone technology in quantifying jump performance over time. Whilst within-session reliability gives some indication of the reliability of measures, its utility is rather limited as in most cases the researcher and practitioner are interested in repeated use of a device/testing protocol over time, e.g. weeks and months. The within-session reliability reported in the papers reviewed gives no insight into the stability of the technology over time and as such is a major limitation of the methodological approaches taken by the authors of these studies. This within-session limitations could have been mitigated if a between-session/test-retest design was adopted in tandem with the within-session analysis. However, only one research group has taken such an approach over two testing occasions [61], and the researchers did not report any measure of absolute consistency.

A limitation of this study is that more than two testing sessions are needed to determine systematic error in a data set, e.g. if there is an increase in the mean between two testing occasions, it is difficult to understand whether there will be a continued increase or a plateauing effect without a third testing occasion. Further research is certainly needed to quantify absolute consistency across multiple testing occasions to truly understand the stability of smartphone measures of jump height.

**Table 2.** The reliability and validity of iPhone technology with an integrated My Jump app in assessing jump variables

| | Variable | Technology | Validity | Reliability | Cautions |
|---|---|---|---|---|---|
| CMJ | Jump height | iPhone 5s<br>120fps 720p | Very high<br>[10] | Within session (subject) - Good [10]<br>Within session (device) - Excellent [10]<br>Internal consistency (subject) – Excellent [10]<br>Inter-rater – Excellent [10] | Increased variability with female populations [61] |
| | | iPhone 6<br>240fps 720p | Very high<br>[31, 61] | Within session (subject) - Excellent [61]<br>Between session – Good to Excellent [61]<br>Within session (device) - Excellent [31, 61]<br>Internal consistency – Excellent [61]<br>Inter-session – High to Very High [61] | Significant systematic bias (overestimation) between My Jump and take-off velocity method from force platform of 0.78%<br>Test re-test reliability only over two occasions |
| | | iPhone 6s<br>240fps 720p | Very high<br>[51, 154] | Within session (device) - Excellent [51, 154]<br>Intra-rater – Excellent [154] | Overestimation of My Jump at high heights<br>Underestimation of My Jump at low heights |
| | Flight time | iPhone 6s<br>240fps 720p | Very high<br>[51] | Not determined | |
| SJ | Jump height | iPhone 6<br>240fps 720p | Very high<br>[61] | Internal consistency – Excellent [61]<br>Within session (device) - Excellent [61]<br>Inter-session – High to Very High [61] | |
| 20-cm DJ | Jump height | iPhone 6<br>240fps 720p | High [61] | Within session (subject) - Good [72]<br>Within session (device) - Excellent [72] | |
| | Reactive strength Index | iPhone 6<br>240fps 720p | Very high<br>[72] | Within session (device) - Excellent ([72] | |
| | Contact time | iPhone 6<br>240fps 720p | Very high<br>[72] | Within session (device) - Excellent [72] | |
| | Mean power | iPhone 6<br>240fps 720p | Moderate<br>[72] | Within session (device) – Moderate [72] | Caution reliability within session |
| 30-cm DJ | Jump height | iPhone 6s<br>240fps 720p | Very high<br>[154] | Within session (device) - Excellent [154]<br>Intra-rater – Excellent [154] | Underestimation of My Jump across all scores |

| | | | | | |
|---|---|---|---|---|---|
| 40-cm DJ | Jump height | iPhone 6<br>240fps 720p | Very high<br>[61, 72] | Within session (subject) - Moderate (16)<br>Internal consistency – Excellent [61]<br>Within session (device) - Excellent [61, 72]<br>Inter-session – High [61] | |
| | Reactive strength Index | iPhone 6<br>240fps 720p | Very high<br>[72] | Within session (device) - Excellent [72] | |
| | Contact time | iPhone 6<br>240fps 720p | Very high<br>[72] | Within session (device) - Excellent [72] | |
| | Mean power | iPhone 6<br>240fps 720p | Moderate<br>[72] | Within session (device) – Moderate [72] | Caution reliability within session |

### 2.2.3 Important Considerations and Practical Applications

There is a distinct lack of studies pertaining to the validity and reliability of smartphone applications for jump diagnostics, and as such only the My Jump application has been highlighted at any length. As previously stated, it is extremely important as a strength and conditioning practitioner when deciding what jump diagnostics are suitable for physical profiling and monitoring of your athletes that they have a good level of validity and reliability. The My Jump application shows very high levels of both as a practical measure in field-based assessments across a number of key variables including jump height, flight time, contact time and RSI. The application also extremely easy to use on court, in the weight room, on the field and it does not matter what model of iPhone is being used or the user as long as the protocol is being followed.

The assessment of DJ performance using My Jump is one assessment that should be used with caution, as jump height was less consistent than CMJ and SJ heights. This was most likely due to the biological variation associated with the drop jump which is more technically and physically demanding for a subject population of sports science students that may not have been familiar with the test [72].

The validity and reliability of calculated mean power from DJ is also questionable and as such should be utilised with caution. This poor agreement and stability is possibly due to the way it is calculated and the potential for variation in jump strategy affecting its calculation. Further studies are needed to determine the utilisation of mean power in an athletic population that are familiar with DJs of varying intensities.

It is clear however that the evidence is very strong to support the use of the My Jump and My Jump 2 application for assessing jump performance across a variety of subjects, from an active student population to highly trained international-level track athletes, and this is important to note as the subjects and end user populations closely reflect the potential end users of the technology.

# CHAPTER 3: VIDEOGRAPHIC VARIABILITY OF TRIPLE AND QUINTUPLE HORIZONTAL HOP PERFORMANCE

This chapter comprises the following paper published in the Journal of Sports Rehabilitation.

**Reference:**

Sharp, A.P., Neville, J., Diewald, S.N., Oranchuk, D.J., & Cronin, J.B. (2024). Videographic Variability of Triple and Quintuple Horizontal Hop Performance. *Journal of Sports Rehabilitation, 33*(7), 570-581.

## 3.0 Prelude

From Chapter 1 it was stated that multiple hop testing, particularly the QH, was a test that "for all intents and purposes had undergone little scrutiny and therefore would benefit from a great deal of research focus, for example, in determining validity, reliability, and sensitivity." In Chapter 2, it was concluded that all smartphone data up to the time of the review measured performance in vertically oriented jumps; however, it was believed that smartphone technology could offer useful insight into the horizontal, unilateral assessment of reactive strength, such as multiple hops in series. Another limitation identified in Chapter 2 was the absence of authors reporting the test-retest reliability of this technology. The use of within-session reliability was considered of limited value, and understanding the variability associated with using the technology across multiple testing sessions appeared more important. Given these limitations, further research was clearly needed to assess the stability of smartphone technology in quantifying hop performance over greater distances than those previously reviewed. Specifically, this chapter aimed to determine the between-rater, within-rater, and test–retest variability of the temporal events in multiple horizontal hop tests.

## 3.1 Introduction

Physical profiling of the lower limbs is common practice within performance and rehabilitative settings as the development of desirable neuromuscular qualities has shown to be an integral part of athletic success [9, 35, 98, 171] and has strong relationships with determinants of acceleration [68, 79, 117, 119, 121] and maximal velocity [117, 119, 167]. Testing batteries typically involve bilateral vertical jumps to assess ballistic force outputs [12, 108]. Paradoxically, field and court-based sports require high-velocity multi-planar motion in an asymmetric or unilateral-cyclical fashion, such as sprinting, cutting or changing direction. Furthermore, the structural stretch-loads on the musculotendinous system are high and usually performed at high velocity (i.e., fast stretch-shortening muscular actions). Complementary changes in spatiotemporal variables such as ground contact, flight times and resultant step frequencies strongly correlate with athletic performance, particularly sprinting characteristics [119, 120, 129]. Thus, it is essential to adopt assessments describing the required elements of these physiological-mechanical qualities. The utility of multiple hops in series (e.g., TH and QH) has been discussed previously [80, 155]. Briefly, multiple horizontal jumps in series are used to assess total body power and landing mechanics, while also valuable for determining inter-limb asymmetries and RTS status [155]. Additionally, performing these jump types with and without the use of arms can help assess total body versus lower limb qualities [155]. Repeated horizontal jumps appear to have face or logical validity, as the demand and skill required for their success closely resemble field and court-based sports involving high velocity, cyclical expressions of unilateral propulsive and braking forces. Evaluating athlete capacity for the spatiotemporal characteristics of these tests through assumption could have strong diagnostic potential for physical performance. However, the absolute and relative consistency of temporal event detection using video for dynamic tasks such as multiple hops in series is not determined and requires further investigation.

The diagnostic value of low-cost 2-D smartphone or tablet video technology for field-based assessments, integrated with low-cost or open-source digitising software, can provide meaningful information to researchers and practitioners outside of a laboratory [10, 14, 61, 70, 72, 80, 128], and has become increasingly accessible [127]. If valid and reliable, smartphone video can provide high practicality in performance settings by offering greater affordability and practicality than 3-D motion analysis. Recent advancements in mobile phone technology (e.g., high frame rates and screen resolutions) have resulted in an exponential increase in their use in sports performance, health, wellness, and medical cohorts and show promising levels of absolute and relative consistency and concurrent validity across populations when deriving jump heights from temporal events of vertically orientated jumps [10, 31, 51, 61, 72, 127, 128, 148, 154].

The absolute and relative consistency and the utility of multiple hop protocols have previously been discussed [155] in which the authors highlight the value of hop testing protocols in athletic performance testing batteries. Hop-based testing in injury rehabilitation is common in the literature, but such performance tests are seldom assessed via video-capture, but simply by jump distance. Six studies have reported absolute and relative consistency of tape measure assessed jump distance during multiple hop protocols with athletes (CV = 1.8-1.9%, ICC = 0.80-0.98) [23, 69, 103, 115, 122, 132]. However, to our knowledge, no studies have investigated the consistency of video for detecting temporal parameters (timing events) of multiple hops. Instead, previous investigations have focused exclusively on vertically orientated jumps [10, 31, 51, 61, 72, 128, 154]. These vertical jump studies reported excellent within-session consistency (CV = 4.6-7.6%, ICC = 0.97-0.997), within-rater rank order consistency (ICC = 0.99), and between-rater absolute and relative consistency (CV = 5.8%, ICC = 0.97-0.99) [10, 31, 51, 61, 72, 128, 154]. There have been limited reports of test-retest consistency of video-graphic jump-based testing. Only a single study reported variability over two testing occasions and showed good levels of relative consistency (*r* = 0.76-0.93) [61]. Understanding the variability associated with repeated video technology/device use over multiple testing sessions would seem more robust and practically meaningful for determining performance changes and rehabilitative progress. Therefore, this technical report aimed to determine the between, within-rater, and test-retest variability of TH and QH temporal events using affordable and accessible video capture (iPad Pro) and digitising (Kinovea 0.8.27) products. If found reliable, such technology could provide a practical means of quantifying temporal events in field-based assessments.

## 3.2 Materials and Methods

### 3.2.1 Experimental Design

Temporal variability parameters were determined by testing nine male athletes over three testing occasions separated by at least three days. A single rater repeated the analysis of the first day on two more occasions seven days apart to determine within-rater variability. Six raters were assigned to detect all associated temporal events from the same video footage to determine between-rater variability. A single rater also analysed video from days 1, 2 and 3 to determine the test-retest variability of the hopping tasks. All variability measures were calculated in the same way, with percentage change in the mean, CVs and ICCs calculated between testing and analysis occasions to assess the stability of measures.

### 3.2.2 Participants

Nine male athletes (20.8 ± 1.3 years, 71.4 ± 9.8 kg and 171.7 ± 4.5 cm) volunteered to participate across various university sports teams and clubs (kendo, baseball, rowing, long jumping). We required all participants to be healthy and injury-free at the time of testing. Potential participants were excluded if they had significant historical injuries (e.g., previous ruptures or tears to major tendons or ligaments [Achilles, ACL]), regardless of post-injury training time. Study procedures followed the Declaration of Helsinki, and study ethical approval was granted by the Auckland University of Technology review board (Appendix I). Informed voluntary consent was attained before inclusion in the study (Appendix IV). Body mass was measured to the nearest 0.1 kg, and height was measured according to the methodology set out by the International Society for the Advancement of Kinanthropometry [123] on a digital scale and stadiometer (Tanita DC-217A, Tokyo, Japan).

### 3.2.3 Procedures

**Multiple Hop Protocol**

A familiarisation session occurred three days before the first testing session, including a standardised warm-up protocol and familiarisation with both TH and QH protocols. Testing procedures were replicated on three occasions, separated by 3-5 (3.7 ± 0.47) days, and completed on a synthetic indoor track surface. The duration between testing sessions was dictated by the athlete's training and playing schedule to account for physical readiness and recovery. Each session began with a standardised 10 min warm-up involving dynamic flexibility exercises for upper and lower limbs to increase core body temperature. The warm-up concluded with explosive bounding movements and progressive sprinting to replicate testing demands. The testing procedure began within five minutes of warm-up cessation.

After the standardised warm-up, each multiple hop trial started with the subject balanced on their trial leg before propelling themselves forward for the required number of contacts and subsequent landing. The TH and QH test protocols consisted of an initial single leg jump immediately followed by two, and four hops on the same leg followed by a double foot landing, respectively (Figure 4). Participants were cued to "reach the furthest horizontal distance in the fastest time possible". Contacting the ground with a hand post-landing was permitted if the movement did not result in further steps forward. Upper limb motion was allowed during the hops, replicating motor patterns associated with athletic activities. Three trials for TH and two for QH were completed for both dominant (DOM) and non-dominant (NDOM) limbs in a randomised order. Limb dominance was determined by asking participants which leg they would kick a ball with. All trials were separated by two minutes of passive rest.

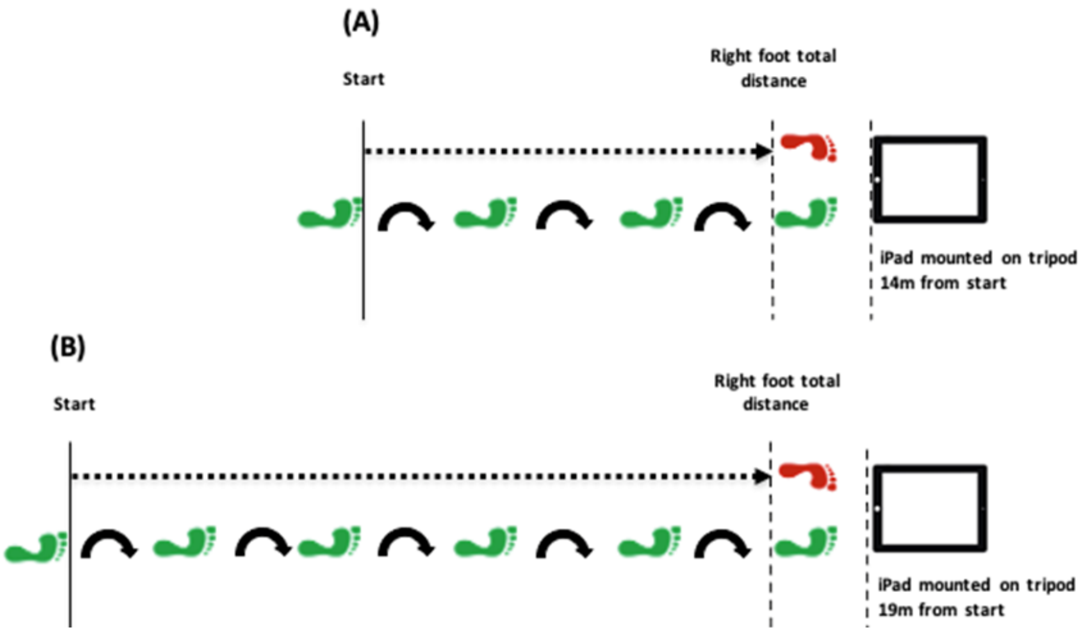


**Figure 4.** Experimental set-up and jump sequence for (A) TH and (B) QH horizontal hop

Videographic data was captured via an iPad Pro (Apple, USA) at 1080 p and 120 fps. The iPad was secured to a tripod at approximately 30 cm height from the ground and positioned at 14 m and 19 m from the start line directly in front of the subject (Figure 5) for TH and QH tests, respectively. Video data was then exported, tagged and stored for further kinematic analysis.

**Figure 5.** Experimental set-up for video capture

## Raters

Six raters participated in the study and were all sports coaches and potential end users of such technology. All raters were novices in using the software (Kinovea 0.8.27) and were provided with a training sheet explaining how to detect each temporal event (Appendix VI). Raters were allowed to ask questions and obtain clarification from the primary investigator, with several years of Kinovea experience, on the protocol before commencing analysis. Previous investigations have reported high levels of validity and reliability in assessing temporal-spatial parameters with 2-D video during various sporting movements [11, 62, 128, 137].

**Assessment of Video Variability**

Each rater analysed the videos by detecting relevant frame numbers at 'toe off' and 'heel strike' for both the TH and QH. 'Toe off' was defined as the first frame after the loss of contact with the ground (Figure 6; A), and 'heel strike' was defined as the first frame of clear ground contact (Figure 6; B). Raters could detect each event by using the slow motion and magnifying tool (2.5x). Frame numbers were logged into a previously designed spreadsheet where flight times, ground contact times and total times were automatically derived via the following formula [FT = flight time (sec); FN = frame number; 119.9 = frame rate].

$$FT = \frac{First\ heel\ strike\ FN - first\ take\ off\ FN}{119.9}$$

**Equation 3.** Flight time calculation

Within-rater (one rater) variability was quantified by taking all testing Session 1 data and analysing over another two occasions separated by ~5-9 (6.9 ± 1.2) days. Between-rater variability was quantified by six raters analysing day-one data only. All six raters determined test-retest variability by comparing the temporal parameters over three testing sessions. All variables (e.g., flight time 1 and ground contact time 2) were taken for each hop and test. This data was then averaged across all participants.

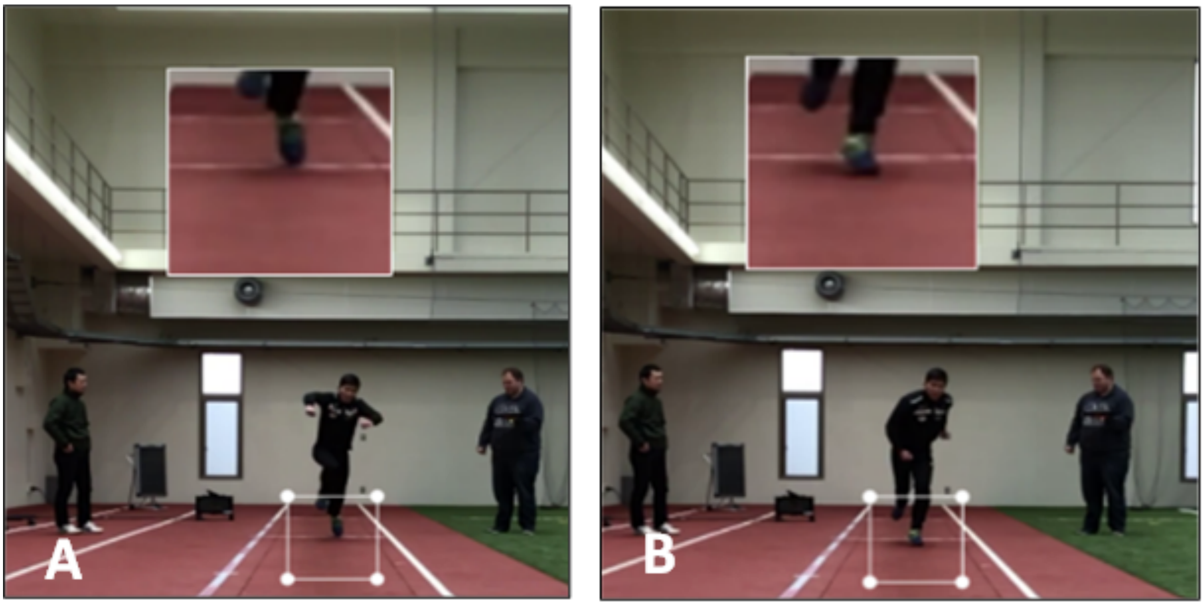


**Figure 6.** Detection of 'toe off' (panel A) and 'heel strike' (panel B) using the Kinovea software program

### 3.2.4 Statistical Analysis

Descriptive statistics, percentage change in the mean, and CV were computed using an online spreadsheet (Microsoft Excel version 1910). Descriptive statistics (means and standard deviations) were used to measure centrality and spread. The Shapiro-Wilk test was used to determine if data were normally distributed. Relative consistency was quantified via ICC, which refers to the consistency of the rank or position of a subject in relation to others [87]. ICCs were calculated using SPSS version 26 (IBM, Armonk, NY, USA) with statistical significance set at an alpha level of $p < 0.05$.

Between-rater variability was determined using a two-way random effects ICC (single rating for absolute agreement). Within-rater variability of a single rater was determined across the three days using a two-way mixed effects ICC (single rating for absolute agreement) on data from the first testing session.

Test re-test variability over three testing occasions was determined using a two-way mixed effects ICC (single rating for consistency). A pairwise *t*-test was used to determine whether DOM and NDOM limbs differed. Greater movement variability was associated with the DOM limb (*p* < 0.05). Therefore, the test-retest variability was determined using DOM limb data only.

ICCs were interpreted as: <0.50 poor relative consistency, ≥0.50 and <0.75 moderate relative consistency, ≥0.75 and <0.90 good relative consistency, and ≥0.90 excellent relative consistency. Percentage change in the mean was calculated as the difference in the group means between days and was reported to indicate the extent to which the average performance differed over testing occasions due to systematic effects (e.g., learning effect) and random effects (e.g., noise) [76]. The SEM was expressed through the CV (%) to determine absolute consistency [7, 76]. A CV < 10% was interpreted as a good level of agreement. Percentage change in the mean was calculated using the following equation:

$$Percentage\ Change = \left(\frac{Mean\ 2\ - Mean\ 1}{Mean\ 1}\right) \times 100$$

**Equation 4.** Percentage change in the mean

## 3.3 Results

The Shapiro-Wilks test determined all variables to be evenly distributed (*p* > 0.05). Between-rater descriptive statistics for each variable and associated measures of consistency between rater measures are presented in Tables 3 and 4. Relative consistency was good to excellent across the six raters (ICC = 0.85-1.00) for the analysis of both DOM and NDOM limbs of TH and QH. Slight improvements in consistency were observed as the subject progressed toward the camera.

Within-rater descriptive statistics of a single rater for each variable and associated measures of consistency for video analysis across the three analysis sessions can be observed in Tables 5 and 6.

The change in the mean for both TH and QH was minimal (-0.8 to 0.7%) and similar between hops for all variables. Absolute (CV = 0.0-2.0%) and relative (ICC = 0.98-1.00) consistency was excellent for all TH and QH variables for the three testing occasions.

The test-retest descriptive statistics and associated variability of measures across testing Days 1-3 are presented in Table 7. Absolute consistency was acceptable across all sessions and variables (CV = 2.0-8.7%) for both TH and QH. TH flight time 1 showed poor levels of consistency (ICC = 0.47) across the three testing days. QH flight times 1 and 2, and TH and QH ground contact time 1 showed moderate consistency (ICC = 0.55-0.60). ICCs were good to excellent in variables later in the hopping cycles (ICC = 0.81-0.93). Total hopping times across the three testing days showed little variability (CV = 2.3-5.0%) and moderate to good levels of relative consistency (ICC = 0.64-0.78).

**Table 3.** Between-rater variability of TH temporal parameters using an iPad Pro and Kinovea at 120 fps

| | **Limb** | **Mean ± SD** | | | | | | **ICC** | **95% CI** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Rater 1** | **Rater 2** | **Rater 3** | **Rater 4** | **Rater 5** | **Rater 6** | | **Lower** | **Upper** |
| FT 1 (s) | NDOM | 0.261 ± 0.03 | 0.245 ± 0.03 | 0.261 ± 0.03 | 0.264 ± 0.03 | 0.259 ± 0.03 | 0.255 ± 0.03 | 0.92 | 0.75 | 0.97 |
| | DOM | 0.268 ± 0.03 | 0.251 ± 0.03 | 0.267 ± 0.02 | 0.269 ± 0.03 | 0.264 ± 0.03 | 0.260 ± 0.03 | 0.86 | 0.63 | 0.94 |
| FT 2 (s) | NDOM | 0.324 ± 0.06 | 0.310 ± 0.06 | 0.323 ± 0.06 | 0.327 ± 0.06 | 0.322 ± 0.06 | 0.316 ± 0.06 | 0.98 | 0.94 | 0.99 |
| | DOM | 0.319 ± 0.06 | 0.308 ± 0.06 | 0.319 ± 0.06 | 0.321 ± 0.06 | 0.318 ± 0.06 | 0.313 ± 0.06 | 0.98 | 0.94 | 0.99 |
| FT 3 (s) | NDOM | 0.448 ± 0.05 | 0.434 ± 0.05 | 0.446 ± 0.05 | 0.446 ± 0.05 | 0.445 ± 0.05 | 0.440 ± 0.05 | 0.99 | 0.96 | 1.00 |
| | DOM | 0.432 ± 0.05 | 0.422 ± 0.05 | 0.433 ± 0.05 | 0.434 ± 0.05 | 0.431 ± 0.05 | 0.424 ± 0.05 | 0.97 | 0.94 | 0.98 |
| GC 1 (s) | NDOM | 0.300 ± 0.04 | 0.312 ± 0.04 | 0.300 ± 0.04 | 0.297 ± 0.04 | 0.301 ± 0.04 | 0.308 ± 0.04 | 0.95 | 0.84 | 0.98 |
| | DOM | 0.304 ± 0.04 | 0.317 ± 0.04 | 0.305 ± 0.04 | 0.303 ± 0.05 | 0.305 ± 0.04 | 0.312 ± 0.04 | 0.95 | 0.86 | 0.98 |
| GC 2 (s) | NDOM | 0.270 ± 0.04 | 0.282 ± 0.04 | 0.270 ± 0.04 | 0.268 ± 0.04 | 0.272 ± 0.04 | 0.277 ± 0.04 | 0.96 | 0.87 | 0.99 |
| | DOM | 0.286 ± 0.04 | 0.294 ± 0.04 | 0.283 ± 0.04 | 0.281 ± 0.04 | 0.284 ± 0.04 | 0.290 ± 0.04 | 0.97 | 0.90 | 0.99 |
| TT (s) | NDOM | 1.60 ± 0.16 | 1.58 ± 0.17 | 1.60 ± 0.16 | 1.60 ± 0.16 | 1.60 ± 0.16 | 1.60 ± 0.16 | 1.00 | 0.99 | 1.00 |
| | DOM | 1.61 ± 0.17 | 1.59 ± 0.17 | 1.61 ± 0.17 | 1.61 ± 0.17 | 1.60 ± 0.17 | 1.60 ± 0.17 | 0.99 | 0.98 | 1.00 |

**Key:** FT = flight time; GC = ground contact time; TT = total time; SD = standard deviation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval

**Table 4.** Between-rater variability of QH temporal parameters using an iPad Pro and Kinovea at 120 fps

| | Limb | Means ± SD | | | | | | ICC | 95% CI | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Rater 1 | Rater 2 | Rater 3 | Rater 4 | Rater 5 | Rater 6 | | Lower | Upper |
| FT 1 (s) | NDOM | 0.260 ± 0.02 | 0.242 ± 0.03 | 0.259 ± 0.02 | 0.262 ± 0.02 | 0.254 ± 0.02 | 0.249 ± 0.02 | 0.85 | 0.67 | 0.93 |
| | DOM | 0.255 ± 0.02 | 0.236 ± 0.03 | 0.251 ± 0.03 | 0.257 ± 0.03 | 0.250 ± 0.02 | 0.245 ± 0.03 | 0.85 | 0.68 | 0.93 |
| FT 2 (s) | NDOM | 0.301 ± 0.05 | 0.287 ± 0.05 | 0.301 ± 0.05 | 0.302 ± 0.05 | 0.297 ± 0.05 | 0.293 ± 0.05 | 0.98 | 0.94 | 0.99 |
| | DOM | 0.299 ± 0.04 | 0.282 ± 0.04 | 0.297 ± 0.04 | 0.299 ± 0.04 | 0.291 ± 0.04 | 0.290 ± 0.04 | 0.96 | 0.89 | 0.99 |
| FT 3 (s) | NDOM | 0.318 ± 0.06 | 0.306 ± 0.06 | 0.317 ± 0.06 | 0.318 ± 0.06 | 0.313 ± 0.06 | 0.309 ± 0.06 | 0.99 | 0.97 | 1.00 |
| | DOM | 0.313 ± 0.05 | 0.300 ± 0.05 | 0.312 ± 0.05 | 0.313 ± 0.05 | 0.307 ± 0.05 | 0.305 ± 0.05 | 0.98 | 0.94 | 0.99 |
| FT 4 (s) | NDOM | 0.334 ± 0.06 | 0.317 ± 0.06 | 0.333 ± 0.06 | 0.336 ± 0.06 | 0.331 ± 0.06 | 0.327 ± 0.06 | 0.98 | 0.94 | 0.99 |
| | DOM | 0.327 ± 0.04 | 0.312 ± 0.04 | 0.326 ± 0.04 | 0.327 ± 0.04 | 0.323 ± 0.04 | 0.319 ± 0.04 | 0.97 | 0.91 | 0.99 |
| FT 5 (s) | NDOM | 0.463 ± 0.06 | 0.450 ± 0.06 | 0.460 ± 0.06 | 0.460 ± 0.06 | 0.456 ± 0.06 | 0.453 ± 0.06 | 0.97 | 0.95 | 0.99 |
| | DOM | 0.453 ± 0.05 | 0.438 ± 0.05 | 0.449 ± 0.05 | 0.450 ± 0.05 | 0.447 ± 0.05 | 0.443 ± 0.05 | 0.98 | 0.95 | 0.99 |
| GC 1 (s) | NDOM | 0.282 ± 0.03 | 0.296 ± 0.03 | 0.282 ± 0.03 | 0.281 ± 0.03 | 0.288 ± 0.03 | 0.291 ± 0.03 | 0.92 | 0.82 | 0.97 |
| | DOM | 0.290 ± 0.02 | 0.305 ± 0.03 | 0.292 ± 0.03 | 0.288 ± 0.02 | 0.294 ± 0.02 | 0.299 ± 0.02 | 0.89 | 0.75 | 0.95 |
| GC 2 (s) | NDOM | 0.253 ± 0.02 | 0.266 ± 0.03 | 0.253 ± 0.02 | 0.252 ± 0.02 | 0.258 ± 0.03 | 0.262 ± 0.02 | 0.92 | 0.79 | 0.97 |
| | DOM | 0.254 ± 0.03 | 0.268 ± 0.03 | 0.255 ± 0.03 | 0.253 ± 0.03 | 0.263 ± 0.03 | 0.263 ± 0.03 | 0.92 | 0.79 | 0.97 |
| GC 3 (s) | NDOM | 0.253 ± 0.02 | 0.268 ± 0.03 | 0.253 ± 0.02 | 0.252 ± 0.02 | 0.257 ± 0.03 | 0.261 ± 0.02 | 0.87 | 0.74 | 0.94 |
| | DOM | 0.250 ± 0.03 | 0.264 ± 0.03 | 0.250 ± 0.03 | 0.248 ± 0.03 | 0.253 ± 0.03 | 0.256 ± 0.03 | 0.95 | 0.85 | 0.98 |
| GC 4 (s) | NDOM | 0.253 ± 0.03 | 0.267 ± 0.03 | 0.253 ± 0.03 | 0.252 ± 0.03 | 0.256 ± 0.03 | 0.260 ± 0.03 | 0.93 | 0.84 | 0.97 |
| | DOM | 0.256 ± 0.03 | 0.270 ± 0.03 | 0.257 ± 0.03 | 0.256 ± 0.03 | 0.260 ± 0.03 | 0.264 ± 0.03 | 0.96 | 0.88 | 0.98 |
| TT (s) | NDOM | 2.71 ± 0.25 | 2.69 ± 0.25 | 2.71 ± 0.24 | 2.71 ± 0.25 | 2.71 ± 0.25 | 2.70 ± 0.25 | 1.00 | 1.00 | 1.00 |
| | DOM | 2.70 ± 0.20 | 2.67 ± 0.20 | 2.69 ± 0.21 | 2.69 ± 0.20 | 2.69 ± 0.21 | 2.68 ± 0.21 | 1.00 | 0.99 | 1.00 |

**Key:** FT = flight time; GC = ground contact time; TT = total time; SD = standard deviation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval

**Table 5.** Within-rater variability of TH temporal parameters using an iPad Pro and Kinovea at 120 fps

| | Limb | Mean ± SD | | | Change in mean (%) | | CV (%) | | ICC | 95% CI | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Session 1 | Session 2 | Session 3 | 2-1 | 3-2 | 2-1 | 3-2 | | Lower | Upper |
| FT 1 (s) | NDOM | 0.261 ± 0.04 | 0.260 ± 0.04 | 0.260 ± 0.04 | -0.6 | 0.1 | 1.5 | 0.5 | 0.99 | 0.99 | 1.00 |
| | DOM | 0.268 ± 0.03 | 0.266 ± 0.03 | 0.268 ± 0.03 | -0.6 | 0.7 | 1.7 | 1.3 | 0.98 | 0.97 | 0.99 |
| FT 2 (s) | NDOM | 0.324 ± 0.06 | 0.323 ± 0.06 | 0.323 ± 0.06 | -0.7 | 0.0 | 1.3 | 0.8 | 1.00 | 0.99 | 1.00 |
| | DOM | 0.319 ± 0.06 | 0.318 ± 0.06 | 0.319 ± 0.06 | -0.4 | 0.4 | 1.3 | 0.9 | 1.00 | 0.99 | 1.00 |
| FT 3 (s) | NDOM | 0.448 ± 0.05 | 0.448 ± 0.06 | 0.449 ± 0.06 | 0.0 | 0.2 | 0.7 | 0.5 | 1.00 | 0.99 | 1.00 |
| | DOM | 0.432 ± 0.05 | 0.433 ± 0.05 | 0.433 ± 0.05 | 0.2 | 0.1 | 1.1 | 0.5 | 1.00 | 0.99 | 1.00 |
| GC 1 (s) | NDOM | 0.300 ± 0.04 | 0.301 ± 0.04 | 0.301 ± 0.04 | 0.2 | 0.0 | 1.4 | 0.0 | 0.99 | 0.99 | 1.00 |
| | DOM | 0.304 ± 0.04 | 0.304 ± 0.05 | 0.304 ± 0.05 | -0.1 | 0.0 | 1.0 | 0.0 | 1.00 | 0.99 | 1.00 |
| GC 2 (s) | NDOM | 0.270 ± 0.04 | 0.271 ± 0.04 | 0.271 ± 0.04 | 0.3 | -0.1 | 1.0 | 1.2 | 0.99 | 0.98 | 1.00 |
| | DOM | 0.286 ± 0.04 | 0.285 ± 0.04 | 0.285 ± 0.04 | -0.3 | -0.3 | 1.7 | 0.6 | 0.99 | 0.98 | 1.00 |
| TT (s) | NDOM | 1.60 ± 0.16 | 1.58 ± 0.17 | 1.60 ± 0.16 | 0.0 | 0.0 | 0.3 | 0.1 | 1.00 | 1.00 | 1.00 |
| | DOM | 1.61 ± 0.17 | 1.61 ± 0.17 | 1.61 ± 0.17 | -0.1 | 0.1 | 0.2 | 0.2 | 1.00 | 1.00 | 1.00 |

**Key:** FT = flight time; GC = ground contact time; TT = total time; SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval

**Table 6.** Within-rater variability of QH temporal parameters using an iPad Pro and Kinovea at 120 fps

| | Limb | Mean ± SD | | | Change in mean (%) | | CV (%) | | ICC | 95% CI | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Session 1** | **Session 2** | **Session 3** | **2-1** | **3-2** | **2-1** | **3-2** | | **Lower** | **Upper** |
| FT 1 (s) | NDOM | 0.262 ± 0.03 | 0.262 ± 0.03 | 0.260 ± 0.03 | -0.1 | -0.8 | 1.9 | 1.3 | 0.98 | 0.95 | 0.99 |
| | DOM | 0.253 ± 0.03 | 0.253 ± 0.03 | 0.254 ± 0.03 | -0.1 | 0.6 | 1.9 | 1.3 | 0.98 | 0.96 | 0.99 |
| FT 2 (s) | NDOM | 0.308 ± 0.06 | 0.307 ± 0.07 | 0.307 ± 0.07 | -0.5 | 0.1 | 2.0 | 0.6 | 1.00 | 0.99 | 1.00 |
| | DOM | 0.311 ± 0.05 | 0.312 ± 0.05 | 0.312 ± 0.05 | 0.2 | 0.0 | 1.2 | 0.8 | 1.00 | 0.99 | 1.00 |
| FT 3 (s) | NDOM | 0.327 ± 0.07 | 0.326 ± 0.07 | 0.326 ± 0.07 | -0.4 | 0.0 | 1.3 | 0.5 | 1.00 | 1.00 | 1.00 |
| | DOM | 0.327 ± 0.05 | 0.327 ± 0.05 | 0.327 ± 0.05 | -0.1 | 0.1 | 1.9 | 1.2 | 0.99 | 0.98 | 1.00 |
| FT 4 (s) | NDOM | 0.352 ± 0.05 | 0.351 ± 0.05 | 0.352 ± 0.05 | -0.3 | 0.3 | 1.0 | 0.5 | 1.00 | 0.99 | 1.00 |
| | DOM | 0.339 ± 0.05 | 0.340 ± 0.05 | 0.339 ± 0.05 | 0.3 | -0.3 | 0.8 | 0.9 | 1.00 | 0.99 | 1.00 |
| FT 5 (s) | NDOM | 0.465 ± 0.05 | 0.463 ± 0.05 | 0.464 ± 0.05 | -0.4 | 0.2 | 1.1 | 0.4 | 0.99 | 0.99 | 1.00 |
| | DOM | 0.459 ± 0.05 | 0.457 ± 0.05 | 0.458 ± 0.05 | -0.4 | 0.1 | 0.9 | 0.5 | 0.99 | 0.99 | 1.00 |
| GC 1 (s) | NDOM | 0.289 ± 0.04 | 0.289 ± 0.04 | 0.290 ± 0.04 | 0.1 | 0.5 | 1.7 | 0.8 | 0.99 | 0.98 | 1.00 |
| | DOM | 0.290 ± 0.03 | 0.288 ± 0.03 | 0.288 ± 0.03 | -0.6 | -0.1 | 1.3 | 1.3 | 0.98 | 0.96 | 0.99 |
| GC 2 (s) | NDOM | 0.260 ± 0.03 | 0.262 ± 0.03 | 0.262 ± 0.03 | 0.7 | -0.2 | 1.7 | 1.0 | 0.98 | 0.96 | 0.99 |
| | DOM | 0.257 ± 0.03 | 0.257 ± 0.03 | 0.257 ± 0.03 | 0.2 | 0.0 | 1.7 | 1.3 | 0.99 | 0.97 | 0.99 |
| GC 3 (s) | NDOM | 0.259 ± 0.04 | 0.258 ± 0.04 | 0.258 ± 0.04 | -0.1 | -0.2 | 1.0 | 0.5 | 1.00 | 0.99 | 1.00 |
| | DOM | 0.260 ± 0.03 | 0.260 ± 0.03 | 0.260 ± 0.03 | -0.2 | 0.2 | 1.5 | 0.9 | 0.99 | 0.97 | 1.00 |
| GC 4 (s) | NDOM | 0.263 ± 0.03 | 0.264 ± 0.04 | 0.263 ± 0.04 | 0.5 | -0.3 | 1.1 | 0.7 | 0.99 | 0.99 | 1.00 |
| | DOM | 0.265 ± 0.03 | 0.265 ± 0.03 | 0.265 ± 0.03 | -0.1 | 0.0 | 1.3 | 0.9 | 0.99 | 0.98 | 1.00 |
| TT (s) | NDOM | 2.784 ± 0.29 | 2.781 ± 0.29 | 2.781 ± 0.29 | -0.1 | 0.0 | 0.3 | 0.1 | 1.00 | 1.00 | 1.00 |
| | DOM | 2.760 ± 0.24 | 2.759 ± 0.24 | 2.760 ± 0.24 | -0.1 | 0.0 | 0.2 | 0.1 | 1.00 | 1.00 | 1.00 |

**Key:** FT = flight time; GC = ground contact time; TT = total time; SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval

**Table 7.** Test-retest variability (one rater) of TH and QH temporal parameters using an iPad Pro and Kinovea at 120 fps for the dominant limbs

| TH | Means ± SD | | | Change in mean (%) | | CV (%) | | ICC | 95% CI | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Day 1 | Day 2 | Day 3 | 2-1 | 3-2 | 2-1 | 3-2 | | Lower | Upper |
| FT 1 (s) | 0.268 ± 0.027 | 0.254 ± 0.022 | 0.260 ± 0.017 | -5.0 | 2.5 | 4.7 | 6.0 | 0.47 | 0.06 | 0.82 |
| FT 2 (s) | 0.318 ± 0.056 | 0.292 ± 0.038 | 0.307 ± 0.037 | -8.0 | 5.6 | 7.6 | 5.6 | 0.71 | 0.35 | 0.92 |
| FT 3 (s) | 0.432 ± 0.050 | 0.424 ± 0.058 | 0.436 ± 0.049 | -2.2 | 3.2 | 6.6 | 4.5 | 0.81 | 0.54 | 0.95 |
| GC 1 (s) | 0.304 ± 0.043 | 0.295 ± 0.020 | 0.299 ± 0.020 | -2.1 | 1.2 | 6.8 | 3.4 | 0.60 | 0.20 | 0.88 |
| GC 2 (s) | 0.286 ± 0.039 | 0.270 ± 0.028 | 0.269 ± 0.029 | -5.4 | -0.1 | 3.9 | 2.8 | 0.90 | 0.72 | 0.97 |
| TT (s) | 1.608 ± 0.166 | 1.534 ± 0.112 | 1.572 ± 0.080 | -4.4 | 2.6 | 5.0 | 3.0 | 0.64 | 0.25 | 0.89 |

| QH | Means ± SD | | | Change in mean (%) | | CV (%) | | ICC | 95% CI | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Day 1 | Day 2 | Day 3 | 2-1 | 3-2 | 2-1 | 3-2 | | Lower | Upper |
| FT 1 (s) | 0.253 ± 0.032 | 0.253 ± 0.025 | 0.259 ± 0.013 | 0.2 | 2.7 | 6.5 | 5.6 | 0.58 | 0.18 | 0.87 |
| FT 2 (s) | 0.311 ± 0.048 | 0.288 ± 0.039 | 0.297 ± 0.034 | -7.4 | 3.4 | 8.7 | 5.6 | 0.59 | 0.18 | 0.87 |
| FT 3 (s) | 0.327 ± 0.046 | 0.298 ± 0.042 | 0.313 ± 0.049 | -8.9 | 5.0 | 7.7 | 5.1 | 0.81 | 0.52 | 0.95 |
| FT 4 (s) | 0.339 ± 0.048 | 0.317 ± 0.046 | 0.323 ± 0.037 | -6.3 | 2.2 | 5.8 | 5.7 | 0.83 | 0.58 | 0.96 |
| FT 5 (s) | 0.459 ± 0.045 | 0.451 ± 0.057 | 0.448 ± 0.058 | -1.9 | -0.9 | 3.8 | 2.0 | 0.93 | 0.80 | 0.98 |
| GC 1 (s) | 0.290 ± 0.032 | 0.290 ± 0.021 | 0.289 ± 0.022 | 0.3 | -0.5 | 5.7 | 4.5 | 0.55 | 0.14 | 0.86 |
| GC 2 (s) | 0.257 ± 0.033 | 0.253 ± 0.021 | 0.251 ± 0.025 | -1.1 | -0.8 | 5.8 | 4.3 | 0.75 | 0.42 | 0.93 |
| GC 3 (s) | 0.260 ± 0.032 | 0.250 ± 0.029 | 0.240 ± 0.026 | -3.7 | -3.8 | 4.0 | 4.4 | 0.87 | 0.66 | 0.97 |
| GC 4 (s) | 0.265 ± 0.032 | 0.253 ± 0.031 | 0.252 ± 0.030 | -4.4 | -0.5 | 3.8 | 3.4 | 0.93 | 0.79 | 0.98 |
| TT (s) | 2.760 ± 0.242 | 2.653 ± 0.190 | 2.672 ± 0.182 | -3.8 | 0.7 | 3.9 | 2.3 | 0.78 | 0.48 | 0.94 |

**Key:** FT = flight time; GC = ground contact time; TT = total time; SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; 95% CI = 95% confidence interval

## 3.4 Discussion

To the author's knowledge, there has been no previous research quantifying the consistency of detecting temporal parameters (timing events) in multiple hops through video analysis. The main findings of this study were: 1) good to excellent between-rater consistency for analysis of both DOM and NDOM limbs during the TH and QH tests; 2) excellent within-rater consistency in all TH and QH variables; and 3) acceptable test-retest relative consistency for all variables, with 10/16 variables achieving good to excellent consistency over three testing sessions. Therefore, we postulate that the affordable and accessible hardware and software systems in the present study can be widely adopted by sports performance and rehabilitation practitioners and researchers to evaluate many spatiotemporal variables during multiple horizontal hops.

Interestingly, test-retest results of absolute consistency across testing days for both TH and QH (CV = 2.0-8.7%) were acceptable, whereas relative consistency was less so, especially with the variables earlier in the hopping cycle (flight times 1 and 2: ICC = 0.47-0.71, ground contact time 1: ICC = 0.55-0.60). There is no doubt that the sample size affected this statistical analysis, as minor changes in rank order will considerably influence the magnitude of the correlations when subject numbers are small. The ICCs were greater in the latter stages of the hop sequence for both TH and QH, indicating more initial movement variability in these movement patterns. We speculate that this is a function of the initial hop distance (flight time 1) and associated individual movement strategies in novices, where over or under-distance hopping will affect the ability of the neuromuscular system to tolerate the stretch load, which would consequently affect flight and ground contact times.

When utilising videographic tools such as an iPad and Kinovea software, it is important to ensure that similar results can be replicated across users to establish whether different end users can similarly quantify each variable. Excellent levels of between-rater consistency across all variables (ICC = 0.85-1.00) and hops were observed, indicating that the criteria used to define each movement and the technology used to quantify the variables of interest were easily understood. These results are comparable to those reported for vertical jump assessments [10, 51]. Of note is a slightly larger range of confidence intervals (CI) for detecting variables further away from the camera for TH (starting 14 m from the camera) and QH (starting 19 m away from the camera). While absolute consistency at these further distances was good, practitioners should take all reasonable measures to ensure clarity of detection and 'clean' video footage. LED lighting was employed during data collection. However, changes in light due to the time of day and environmental weather were a factor in detecting temporal events. Additionally, footwear colour, which sometimes clashes with the landing surface, can make detection more difficult. Practitioners should be aware that this could influence event detection and, therefore, perceived changes in performance.

Finally, within-rater analysis (ICC = 0.98-1.00) for video footage across time of both TH and QH was consistent with those reported in the vertical jump literature [154]. Therefore, a single rater can produce almost identical results when analysing the same footage on multiple occasions.

Despite a relatively small sample of nine athletes, an iPad Pro and digitizing software programme to detect temporal events in the frontal plane during horizontally orientated hops in series is reliable, especially in measures of absolute consistency. This study complements previous literature reporting the consistency of multiple hops in series [80, 155]. It provides promise for those interested in using simple and affordable technology to measure horizontal explosive capability, which can be as valuable as its vertically orientated and previously determined reliable counterparts [10, 31, 72, 154]. Additionally, Jales et al. reported that single leg TH distance is highly reliable (e.g., ICC = 0.95-0.96) when performed via telehealth [80]. Therefore, it is plausible that temporal variables can be confidently assessed while athletes travel for competitions or perform rehabilitation periods away from their chosen practitioner. Unfortunately, we did not formally record the processing time required by each rater. While we estimate two to three minutes to analyse the TH and QH tests, future reports should formally assess this variable to inform potential users of time costs.

## 3.5 Conclusions

The low-cost but highly available 2-D smartphone/tablet and free-to-use software employed in this study are reliable in detecting temporal events during multiple hops. Therefore, practitioners can confidently assess multiple hop horizontal tests, which have previously been reported as valuable when monitoring physical performance, fatigue, and injury management. Practitioners should be mindful of providing adequate familiarisation and standardisation of methodology. In particular, the placement height of the camera must ensure precise detection of ground contacts.

# CHAPTER 4: COMPARISON OF MULTIPLE HOP TEST KINEMATICS BETWEEN FORCE PLATFORMS AND VIDEO FOOTAGE: A CROSS-SECTIONAL STUDY

This chapter comprises the following paper published in the International Journal of Kinesiology and Sports Science.

**Reference:**

Sharp, A.P., Cronin, J.B., Neville, J., Diewald, S.N., Stolberg, M., Draper, N. & Walter, S. (2023). Comparison of Multiple Hop Test Kinematics Between Force Platforms and Video Footage: A Cross-Sectional Study. *International Journal of Kinesiology and Sports Science, 11*(3), 23-28.

## 4.0 Prelude

In Chapter 3, it was found that low-cost but highly available 2-D smartphone/tablet and free-to-use software were reliable for detecting temporal events associated with multiple hops testing. However, the validity of horizontal hopping assessments in the frontal plane using mobile phone or tablet applications had not been reported. Therefore, the current study aimed to determine the validity of using a mobile device application to measure kinematic variables of horizontal multiple hops in series and compare these with gold-standard force platform technology. If the study results show that assessing multiple hops with mobile tablets is valid, then, along with the findings from Chapter 3, this approach could be recommended as a reliable and valid option for sports coaches seeking to assess multiple hop performance.

## 4.1 Introduction

Hopping based tests such as TH and QH are valid and reliable tests to measure physical fitness among athletic populations [155]. Both tests have been used to assess stretch load tolerance and unilateral propulsive and braking force capability [9, 35, 68, 98, 171] of athletic populations. Kinematic outputs measured during multiple hop assessments such as ground contact time, flight time and resultant step frequencies have shown strong correlations with measures of athletic performance, and particularly with sprinting characteristics [119, 120, 129]. Therefore, multiple hop assessments could provide valuable diagnostic information for athlete profiling.

The kinetic and kinematic outputs of multiple hop assessments have ordinarily been determined using force platforms, accelerometers, and high-velocity motion capture cameras, with the force platform assessment method widely acknowledged as the gold standard. However, lack of affordability and access to force platforms is a limiting factor for coaches working in community-level athlete development programmes. The availability of a valid, reliable, low-cost and accessible technology would be ideal for coaches seeking to assess multiple hops in series practically on-field rather than in a laboratory setting.

A recent review of the utility of mobile phone or tablet device applications for measuring athlete vertical jumping height has shown high levels of validity and reliability [148]. Vertical jump data captured using mobile device applications have previously been compared with force platform data and shown high validity ($r$ = 0.60-0.995) [10, 31, 51, 61, 154]. However, the validity and reliability of horizontal hopping assessments in the frontal plane using mobile phone or tablet device applications have not been reported. Therefore, this study aimed to determine the validity of utilising a mobile device application to measure kinematic variables of horizontal multiple hops in series and compare these with force platform gold-standard technology.

## 4.2 Methods

### 4.2.1 Participants and Study Design

Using an observational cross-sectional study design, male university athletes (n = 44; mean ± standard deviation descriptive data, age: 20.1 ± 1.4 years; weight: 71.2 ± 8.6 kg; height: 171.9 ± 5.1 cm) of various sporting success and codes participated in the study. A participant classification framework identified them at a range of Tier 0-3 [107]. Inclusion criteria required all participants to be healthy and injury-free at the time of testing, with no history of major reconstructive surgery of the lower limb or significant historical injuries that could affect performance in the previous two years. Ethical approval was granted by the Auckland University of Technology Ethics Committee [Appendix I (reference: 17/133)]. The participating athletes provided their written informed voluntary consent prior to testing.

### 4.2.2 Study Design

**Multiple Hop Performance**

A hopping familiarisation session was conducted for all athletes three days prior to the testing. Familiarisation included a warm-up consisting of explosive bounding movements to replicate testing demands and progressive sprinting over 30 m. The athletes executed both the TH and QH on a series of force platforms, while being video recorded simultaneously. Each multiple hop trial started with the athlete balanced on their trial leg before propelling themselves forward for the required number of contacts and subsequent landing. The TH test protocol consisted of two hops on the same leg followed by a double foot landing, and the QH test consisted of four hops on the same leg followed by a double foot landing. Athletes were cued to “reach the furthest horizontal distance in the fastest time possible”. Contact on the ground with the athlete’s hands post-landing was permitted if the movement did not result in further steps forward. Upper limb motion was allowed during the hops, replicating motor patterns associated with athletic movements. All athletes completed three trials for TH and two trials for QH on both their DOM and NDOM limbs in a randomised order with two minutes rest between efforts. Only two repetitions of the QH were performed on each leg due to the very high stretch-load demands and to reduce any significant effects of fatigue on performance.

### 4.2.3 Equipment

**Force Platform**

Athletes performed multiple hops in series on a synthetic indoor track surface covering a series of embedded inground force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan) covering the entire hopping distance. The force platforms collected ground reaction forces (GRFs) at a sampling rate of 1000 Hz by connecting to a single computer. GRF force data was processed as described in previous studies investigating temporal events [119] using embedded force platforms in series. The GRF signals collected during the hop trials were filtered using a 4th-order Butterworth low-pass digital filter with a cut-off frequency of 50 Hz. Hop temporal events, including ground contact, flight and total times, were identified by a vertical GRF threshold set at 20 N in a purpose-built algorithm (MATLAB R2021a, The Mathworks Inc, Massachusetts, USA).

**Video Analysis Mobile Device Application**

To record the multiple hops in series, an iPad Pro A1584/1652 (Apple Inc, Cupertino, CA, USA) was used. The iPad recorded the multiple hops at 1080 p and 120 fps secured on a tripod at 30 cm height above the ground and positioned at 14 m and 19 m from the start line, directly in front of the athlete for TH and QH tests, respectively. The video footage and force platform data were obtained simultaneously. The video footage recorded using the iPad was processed using the Kinovea application. This application has been used to analyse kinematic parameters in several athletic jumping performance studies [11, 62, 134, 137].

**Video Footage Analysis**

The event of 'toe off' was defined as the first frame after loss of contact with the ground, and the event of 'heel strike' was defined as the first frame of clear ground contact in line with previously documented methods using Kinovea [11]. Ground contact and flight times were determined by the interval of detection of 'toe off' and the subsequent 'heel strike' for both TH and QH. A slow motion and magnifying tool (2.5x) built into the Kinovea application was used to simplify the detection of each event. Frame numbers were logged into a spreadsheet (Microsoft Excel, Microsoft Corporation, Washington, USA) in which flight times, ground contact times and total times were automatically calculated.

### 4.2.4 Statistical Analysis

Descriptive statistics (estimated mean, mean differences, and CI) were reported for all statistical comparisons. Assumption checks for homogeneity, linearity and normality of residuals were determined to be acceptable for both TH and QH data across methods. The validity of video footage measures against the force platform data was determined by several statistical tests. Firstly, a linear mixed-effect model was used to compare any differences in variables across limbs, methods, trials, and athletes. Statistical significance was set at an alpha level of $p < 0.05$. Effect sizes (ES) were reported using Cohen's *d*, and interpreted as very small (< 0.2), small (0.21-0.5), moderate (0.51-0.79) and large (> 0.8) [36]. Secondly, the linear mixed-effect model was used to determine any bias between the force platform and video footage. Flight times and ground contact times were specified as the dependent variable in each analysis, between force platform and video footage, hops (3 or 2 per leg), and their interaction were specified as fixed effects. A nested random intercept structure was specified for the random effect, with trials nested within the athletes' repeated measures. Thirdly, further visual representation of the level of agreement and any bias between the force platform and video footage as the method of analysis was constructed using Bland-Altman plots [22], where the differences between methods were plotted against their averages (force platform – video footage), and the 95% limits of agreement [21]. Fourth, to establish the concurrent validity between the iPad footage and the force platform data, an ICC with 95% CI was calculated for ground contact times, flight time and total time for both the TH and QH. All statistical analyses were performed using RStudio (version 1.4.1103, PBC, Boston, USA) and Microsoft Excel 2016 (Microsoft Corp, USA).

## 4.3 Results

No significant differences ($p < 0.05$) were observed between data for DOM and NDOM limbs during TH and QH, and so all trials were pooled for analysis to compare methods. Estimated means, standard deviations and 95% CI are shown for flight and ground contact for both TH and QH in Table 8.

Visual analysis of Bland-Altman plots showed the between method differences (force plate versus video) for flight times, ground contact times and total times were consistent across the hops and that the majority of the data points are within the 95% CI. There were notable differences (Table 9) in flight time which decreased with both the TH (-0.015, -0.012, -0.008 s) and QH (-0.016, -0.013, -0.013, -0.011, -0.009 s) as the athlete came closer to the iPad, however, the ES for the differences in flight time were very small (0.08-0.017) and not statistically significant. Ground contact times from the video footage were consistently overestimated in comparison to the force plate across both TH and QH. Interestingly these differences (0.013 to 0.014 s) showed very small changes across hops and as the participant hopped came closer to the iPad. These differences were small (0.21-0.29) and not statistically significant.

In summary, there is a systematic bias between the two methods of analysis, but the bias is uniform (between DOM and NDOM limbs, and across trials and hops). Bland-Altman comparisons indicated a good level of agreement between the video footage and force platform, with mean bias across all variables ranging from 0.009 to 0.016 s which represents approximately 1-2 video frames at 120 Hz.

**Table 8.** Estimated means and standard deviations (95% CI) of hop kinematics between the force platform and video footage

| | | **Force platform** | | **iPad video footage** | |
|---|---|---|---|---|---|
| | | Mean ± SD | CI low-high | Mean ± SD | CI low-high |
| TH FT | 1 | 0.281 ± 0.038 | 0.265 – 0.295 | 0.266 ± 0.040 | 0.250 – 0.280 |
| | 2 | 0.330 ± 0.056 | 0.314 – 0.344 | 0.318 ± 0.056 | 0.302 – 0.333 |
| | 3 | 0.441 ± 0.052 | 0.425 – 0.455 | 0.433 ± 0.055 | 0.417 – 0.447 |
| QH FT | 1 | 0.277 ± 0.035 | 0.263 – 0.294 | 0.261 ± 0.037 | 0.247 – 0.277 |
| | 2 | 0.317 ± 0.053 | 0.303 – 0.334 | 0.304 ± 0.053 | 0.290 – 0.321 |
| | 3 | 0.327 ± 0.049 | 0.313 – 0.344 | 0.314 ± 0.050 | 0.300 – 0.331 |
| | 4 | 0.345 ± 0.048 | 0.331 – 0.362 | 0.334 ± 0.048 | 0.320 – 0.351 |
| | 5 | 0.447 ± 0.061 | 0.432 – 0.463 | 0.437 ± 0.064 | 0.423 – 0.454 |
| TH GCT | 1 | 0.281 ± 0.036 | 0.270 – 0.291 | 0.295 ± 0.037 | 0.284 – 0.305 |
| | 2 | 0.260 ± 0.035 | 0.249 – 0.270 | 0.273 ± 0.038 | 0.262 – 0.282 |
| TH GCT | 1 | 0.273 ± 0.032 | 0.263 – 0.282 | 0.287 ± 0.033 | 0.277 – 0.296 |
| | 2 | 0.244 ± 0.029 | 0.234 – 0.253 | 0.258 ± 0.030 | 0.249 – 0.268 |
| | 3 | 0.239 ± 0.030 | 0.229 – 0.248 | 0.252 ± 0.030 | 0.242 – 0.261 |
| | 4 | 0.241 ± 0.032 | 0.231 – 0.250 | 0.253 ± 0.032 | 0.244 – 0.263 |

**Key:** Mean ± SD presented in seconds; CI = confidence interval; TH = triple hop; QH = quintuple hop; FT = flight time; GCT = ground contact time

**Table 9.** Mean difference (95% CI) of hop kinematics between the force platform and video footage

| | | Difference | CI low-high | *p* | *d* | Interpretation |
|---|---|---|---|---|---|---|
| TH FT | 1 | -0.015 | -0.020 to -0.010 | < 0.001 | 0.17 | trivial |
| | 2 | -0.012 | -0.016 to -0.007 | < 0.001 | 0.14 | trivial |
| | 3 | -0.008 | -0.013 to -0.004 | 0.001 | 0.10 | trivial |
| QH FT | 1 | -0.016 | -0.023 to -0.010 | < 0.001 | 0.13 | trivial |
| | 2 | -0.013 | -0.020 to -0.007 | < 0.001 | 0.11 | trivial |
| | 3 | -0.013 | -0.020 to -0.007 | < 0.001 | 0.11 | trivial |
| | 4 | -0.011 | -0.017 to -0.004 | 0.002 | 0.09 | trivial |
| | 5 | -0.009 | -0.016 to -0.003 | 0.005 | 0.08 | trivial |
| TH GCT | 1 | 0.014 | 0.011 to 0.017 | < 0.001 | 0.29 | small |
| | 2 | 0.013 | 0.009 to 0.016 | < 0.001 | 0.27 | small |
| QH GCT | 1 | 0.014 | 0.011 to 0.018 | < 0.001 | 0.24 | small |
| | 2 | 0.014 | 0.011 to 0.018 | < 0.001 | 0.24 | small |
| | 3 | 0.013 | 0.009 to 0.017 | < 0.001 | 0.22 | small |
| | 4 | 0.013 | 0.009 to 0.016 | < 0.001 | 0.21 | small |

**Key:** Difference presented in seconds; Statistical significance set at an alpha level of $p < 0.05$; CI = confidence interval; TH = triple hop; QH = quintuple hop; FT = flight time; GCT = ground contact time; Cohen's d ES are trivial if d ≤ 0.2, small if d = 0.2 - 0.6

## 4.4 Discussion

This study aimed to determine the validity of utilising a mobile device with Kinovea to assess kinematic variables of horizontal multiple hops in series, and compare these with force platform gold-standard technology. To the author's knowledge, such a methodology had not been investigated previously, and so difficult to compare with other studies. However, the high level of agreement between video and force platform is consistent with that seen in vertically orientated jump assessments. The main findings of this study were: 1) there were significant differences ($p < 0.05$) between hop variables captured from an iPad video compared to force plate; 2) there was a consistent underestimation in flight times seen across TH (-0.015 to -0.008 s) and QH (-0.016 to -0.009 s) which corresponded to the distance the subject was away from the iPad, although these differences were not significantly different across flight times; 3) iPad video over estimated (0.013 to 0.014 s) ground contact times for both TH and QH similarly, regardless of distance away from the subject; and, 4) although there were significant differences in both flight times and ground times between methods, the differences were consistent and a systematic bias was observed between methods.

From the results of this study, it appears that whilst the iPad video provided a valid alternative to force plate technology, the results were not comparable without some form of statistical correction. It is likely that the differences observed in terms of the systematic bias are due to the methods used to quantify each flight and contact times. Video-determined variables can only be defined by either ‘contact’ or ‘no contact’ in the selection of heel strike and toe off, and limited to a sampling rate of 120 fps, whilst force plate data can be collected at 1000 Hz, but can only be measured while there is contact. This contact must also be higher than the unloaded noise of the force plate, and thus a 20 N threshold is used in an aim to reduce that noise. These methodological/technological differences no doubt explain some of the observed bias.

The small but insignificant under-estimations seen in flight times can be attributed to the increased difficulty in detecting heel strike and toe off due to potential perspective error at distances further away from the iPad. Of interest and difficult to explain was the observation that greater differences were not observed during QH analysis when the camera was at an increased distance of 19 m from the athlete. We hypothesised that these differences are most likely accounted for by the period of flight time as opposed to the distance from the camera, which would also account for the consistency in the ground contact times seen across both TH and QH. Therefore, coaches can use video footage recorded using an iPad pro with the Kinovea application to accurately measure their athletes’ kinematic multiple horizontal hop data.

## 4.5 Limitations of the Study

Anecdotally, the researchers noted that whilst all reasonable measures were taken to ensure clarity of detection by way of artificial LED lighting sources, ‘clean’ video footage, and the video identification of heel strike and toe-off requiring visual light to be seen under the foot meant that some trials were more difficult to determine than others due to changes in environmental lighting conditions and colour of participant footwear. Interestingly, this difficulty was not proven to be statistically significant.

## 4.6 Practical Implications of the Study

Multiple hops are movements that stress the neuromuscular system more so than most jumps due to the cyclic unilateral higher stretch loads of the consecutive hopping movements. As a movement screening diagnostic tool, it can be thought of as a progressive assessment in relation to many in-place acyclic jumps, providing advanced insights into injury risk, movement competency, and performance capability.

Until this study total distance was one of the only metrics used to interpret multi-hopping ability. We found a simple and cost-effective solution to capturing advanced diagnostics to provide a more granular approach to understanding high load SSC performance. Inter-step and inter-limb comparisons in terms of flight, contact and total time in conjunction with total distance can provide detailed insight into movement strengths and weaknesses. Furthermore, the inter-jump comparisons have been suggested to provide insight into accurate assessments of cyclical expressions of strength that are closely linked to the accelerative and maximal speed capacity of an athlete. Whilst this study does not provide a kinetic understanding of the hopping movements, the procedures could be utilised to determine a deeper understanding of injury risk and asymmetry during return to play protocols post injury, and high-end neuromuscular performance in the non-injured.

As an aside, a couple of observations were made in terms of inter-hop and inter-jump comparisons. Ground contacts could be classified as high stretch-load movements (average = 0.259 s) given the magnitude and rate of unilateral loading. As high as 6100 N in the fourth hop of a QH were seen in this study for a 70 kg athlete, which equates to approximately 8.9 x bodyweight loaded unilaterally over 0.192 seconds. As such, TH and QH are thought useful assessments of cyclical expressions of strength that are closely linked to the accelerative and maximal speed capacity of an athlete. And finally, it seems as though both TH and QH have similar spatiotemporal demands, however further insight into the kinetics of multiple hops and associated neuromuscular demands is needed to fully understand the mechanics, utility and adaptive potential of these exercises.

## 4.7 Conclusions

Assessing an athlete’s horizontal multiple hops in series performance is important for physical performance coaches. The current study determined that TH and QH performances of athletes can be reliably, accurately, and cost-effectively measured using an iPad tablet with the Kinovea application. This study’s findings may help community-level coaches who want to measure their athletes’ horizontal multiple hop performance in an affordable and valid way.

# CHAPTER 5: STRETCH-LOAD DEMANDS IN MULTIPLE HOPS: IMPLICATIONS FOR ATHLETIC PERFORMANCE AND REHABILITATION

This chapter comprises the following paper submitted to the European Journal of Sports Science.

**Reference:**

Sharp, A.P., Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Stretch-load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation. *In review.*

## 5.0 Prelude

The earlier chapters of this thesis focused mainly on describing the kinematic demands of multiple hopping. While this provides useful insight into how these movements are performed, equally important is determining the kinetic demands to further understand their potential application in athlete rehabilitation and physical preparation. A key practical challenge is that capturing these forces over multiple hops usually requires a minimum of 20 m of in-ground force plates. To address this gap, kinetic data were collected at the National Institute of Fitness and Sport in Japan, a facility equipped with 50 m of in-ground force plates, an infrastructure rarely available in the existing literature. The present study sought to quantify and compare the kinetic demands of multiple hopping tasks performed in series. Particular emphasis was placed on elucidating the incremental loading demands associated with the QH task relative to the more widely studied TH, with additional consideration given to the stretch-load characteristics associated with each hopping variant.

## 5.1 Introduction

The ability to express cyclical and rapid stretch-shortening (eccentric-concentric) muscular actions like jumping, landing, and change-of-direction is beneficial for athletic performance [9]. Jumps and hops are commonplace in athletic training and during physical assessment, not only because of their reliability [44, 122, 150, 155] but also due to their strong relationship with these high-demand athletic qualities, likely because they mimic the speed of contraction, neuromuscular firing patterns, and kinetic energy transfer [42, 75, 82, 121, 141, 170, 171]. 'Stretch-load' refers to the physical demand associated with these actions, and practitioners must pay considerable attention to prepare athletes to manage large forces successfully and without fear or increased risk of injury [105, 162].

Multiple hops in series have been shown to have a stronger relationship with acceleration and time to maximum speed in sprinting performance over vertically orientated jumping assessments, possibly due to their similar force vector orientation [82]. The TH and the QH tests and their relationship with sprint performance have therefore been of interest to researchers [68, 103, 104, 121], mostly finding large correlations (*r* = -0.89 to -0.24). There are limited studies investigating the relationship of QH and sprint performance, with a single study from Nesser et al. who reported very large correlations (*r* = -0.81) of 5-step jump test with 40 m sprint time [121]. However, little is known about the kinematic and kinetic demands of multiple hop testing and training, and no studies have investigated the differences in physical demands between TH and QH in either performance or rehabilitative settings.

A significant proportion of the literature on horizontally displaced hops has focused on the need for athlete rehabilitation [23, 58], particularly for anterior cruciate ligament (ACL) knee injuries [91, 97, 124]. These tests have been used in RTS testing batteries to determine the extent of limb asymmetry [131], physical function level, and re-injury risk assessment. However, the relationship between hopping and athletic performance in healthy athletes has received surprisingly little attention [33]. While limb asymmetry is an intuitive concern, researchers have recently suggested that limb symmetry assessments should be used cautiously, as they do not always give a complete picture of preparedness and may underestimate deficits [64]. Total distance achieved in multiple hop assessments may provide insight into readiness and lower limb performance [69]. Still, their determining components (ground contact and flight phase kinematics and kinetics) could provide greater understanding of reactive strength capability [97] and preparedness for requirements of high stretch-load in the lower limb [91]. Aside from this, understanding the intensity (stretch-load demand) of high ground reactions over short time frames, which are synonymous with these tasks, is essential in the management and programming of athletes [25].

Given the scarcity of literature on the kinetic demands of TH and QH, their differences, as well as their clear application in athlete rehabilitation and physical preparation, this study aimed to quantify the stretch-load demands of both TH and QH assessments, with a focus on understanding the increased demands of the QH. Our first hypothesis was that stretch-load demand, specifically braking and propulsive forces, would increase with each ensuing hop during both tests. Our second hypothesis was that hops 3 and 4 of the QH would require significantly greater stretch-load demand than hops 1 and 2 of the TH or QH test. Understanding these movements' biomechanical, specifically stretch-load demands, will enable practitioners to prescribe these jumps more effectively for injury prevention, rehabilitation, and physical performance enhancement.

## 5.2 Materials and Methods

### 5.2.1 Experimental Approach to the Problem

A cross-sectional study, which included repeated measures within-subject research design, was used to determine the braking and propulsive kinetics of multiple hops in series (TH and QH). Subjects attended the laboratory on two occasions: the first occasion to familiarise themselves with the testing procedures and capture participants' information (age, height, body mass, sport participation, limb dominance), and the second occasion to capture GRFs during TH and QH tests. The maximum vertical force, vertical impulse, vertical braking impulse, vertical propulsive impulse, net anterior-posterior impulse, horizontal impulse, horizontal braking impulse, and horizontal propulsive impulse were quantified and statistically analysed.

### 5.2.2 Participants

Forty-four male athletes (age 20.1 ± 1.4 years; body mass 71.2 ± 8.6 kg; stature 171.9 ± 5.1 cm) from across various university sports (kendo, baseball, rowing, track athletics, field athletics, windsurfing, cycling, soccer, basketball) volunteered to participate. All participants were required to be healthy and injury-free at the time of testing. Potential participants were excluded if they had significant historic injuries (e.g., previous ruptures or tears to major tendons or ligaments [Achilles, ACL]), regardless of the post-injury training time. The study procedures followed the Declaration of Helsinki, and ethical approval was granted by the Auckland University of Technology Review Board (reference: 17/133) (Appendix II) and the National Institute of Fitness and Sports in Kanoya Review Board (reference: 8-123) (Appendix II). Informed consent was obtained before inclusion in the study (Appendices IV and V). Body mass was measured to the nearest 0.1 kg, and stature was measured according to the methodology set out by the International Society for the Advancement of Kinanthropometry [123] on a digital scale and stadiometer (Tanita DC-217A, Tokyo, Japan).

### 5.2.3 Testing Procedures

Each participant attended a familiarisation session a minimum of three days before the first testing session. The session included a standardised warm-up protocol repeated before the testing session. The warm-up included dynamic limb flexibility exercises (upper and lower), general movement to raise body temperature, explosive bounding movements to mimic test demands, and gradually intense sprinting over 30 m. The testing process started five minutes after the warm-up was completed.

The TH test protocol involved three hops on the same leg, while the QH test involved five hops on the same leg (Figure 7). Because of the very high stretch-load demands placed on the body by this test, three trials for TH and two trials for QH were completed in a randomised order for DOM and NDOM limbs, minimising the risk of injury, reducing acute overuse, and reducing fatigue effects. There was a two-minute rest period between the efforts before hopping on the other leg.

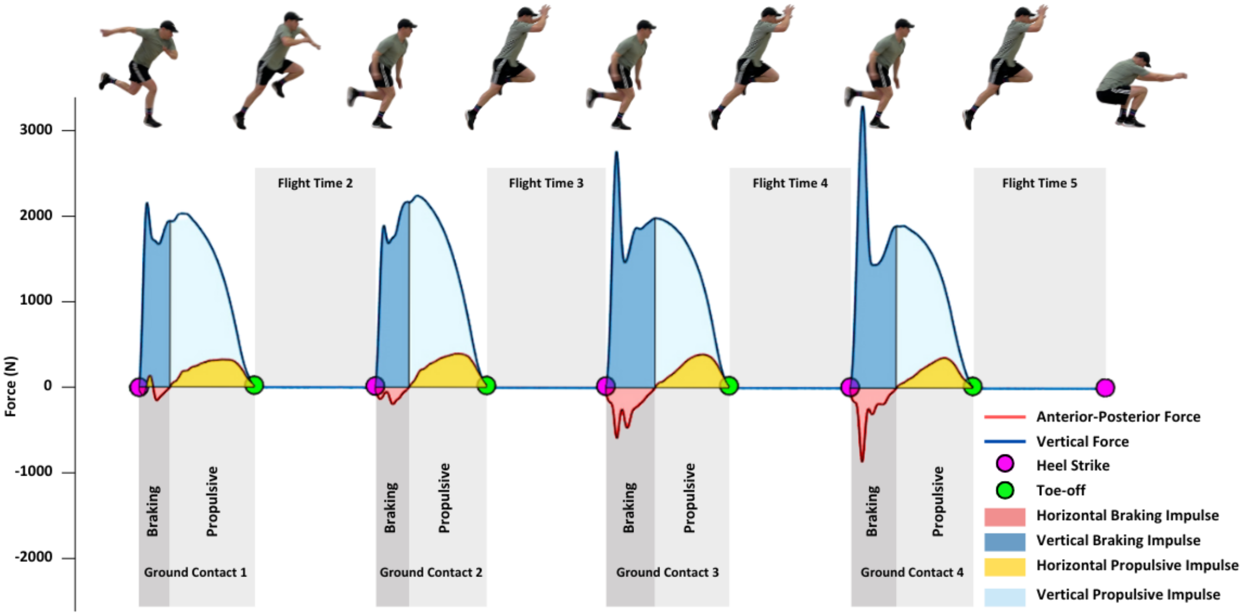


**Figure 7.** Force plate signals of the QH

Each hop began with the subject balancing on their hopping leg before propelling themselves forward for the number of contacts specified in the test. For all tests, the subjects landed on two feet after the final hop; contact with the ground with their hands after landing was permitted if the hopping foot did not move further forward during landing. This was performed to encourage each subject to achieve maximal horizontal displacement. Upper-limb motion was permitted during the hops, replicating the motor patterns associated with athletic movements. Each subject was instructed to "reach the furthest horizontal distance in the shortest possible time”. The hop trials were conducted on an indoor synthetic track surface (Hasegawa Sports Facilities, Tokyo, Japan) that covered 54x inground force platforms in series (TF-90100, Tec Gihan, Kyoto, Japan), and were linked to a single computer that collected GRFs at a sampling rate of 1000 Hz. Force plate data were captured for each trial, exported, tagged, and stored for later analysis. The GRF signals collected during the hop trials were filtered using a 4th-order Butterworth low-pass digital filter with a 50 Hz cutoff frequency, and horizontal and vertical hop propulsive and braking kinetics were determined, with associated impulses calculated via the integration of force for each of the required periods. All variables were computed using a custom algorithm (MATLAB R2021a, Mathworks Inc., Massachusetts, USA). Figure 7 depicts the force and distance signals obtained during a QH trial.

### 5.2.4 Validation of Stretch-load

When defining 'stretch-load' experienced by each participant (absolute measures), vertical braking impulse was thought to be the variable of most interest and the period of stretch-load classified as the moment of initial heel strike to the point of center of pressure (CoP) crosses the zero axis at the anterior-posterior transition, assuming that the subject's CoM was directly above the foot at this point, as previously described [114, 118]. This classification was internally validated with high consistency using a MAC3-D motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA; 250 Hz) to determine agreement between the instance of the participant’s centre of gravity and maximal knee flexion, with the instance of a switch from horizontal braking to horizontal propulsive force and the second peak of the vertical GRF. Both vertical and horizontal braking impulses were determined as the time integration of the GRF during the same period, from the moment of the initial heel strike until the moment the force time curve crosses the zero axis in the anterior-posterior waveform (see Figure 7) and therefore are indicative of the stretch-load associated with each hop.

### 5.2.5 Statistical Analysis

Statistical analyses were conducted using an online spreadsheet (Microsoft Excel version 16.82) and Jeffrey's Amazing Statistics Program (JASP) software (version 0.18.3; Amsterdam, Netherlands). Using descriptive statistics (means and standard deviations), centrality and spread were calculated and are presented in the tables. Assumptions of univariate normality, outliers, and sphericity were assessed. Outlier analysis was conducted using boxplots, and values larger than three standard deviations were manually omitted from further analysis. The Shapiro-Wilk test [145] evaluated normality, and Q-Q plots were used to assess kurtosis and skewness visually.

The kinetic variables of Steps 1 and 2 in TH were compared using a pairwise sampled *t*-test. Statistical significance was set at a $p < 0.05$. ES were reported using Cohen's *d* and categorised as very small (<0.2), small (0.21-0.5), moderate (0.51-0.79), and large (>0.8) [36]. A repeated measures analysis of variance (ANOVA) with one within-subject factor was conducted to determine whether there were significant differences between Steps 1 to 4 in QH. Mauchly’s test was used to assess the assumption of sphericity [102]; if the assumption of sphericity was violated, then Greenhouse-Geisser corrections were applied [66]. Bonferroni post hoc comparisons were used to test the differences in the estimated marginal means for each combination of within-subject effects. ES were reported using partial eta squared ($\eta^2_p$) and categorised as small (0.01), medium (0.06), and large

(0.14). The percentage change in the mean was calculated using the following equation (Equation 5):

$$Percentage\ Change = \left(\frac{Mean\ 2\ - Mean\ 1}{Mean\ 1}\right) \times 100$$

**Equation 5.** Percentage change in the mean

## 5.3 Results

A summary of the absolute kinetic data for all variables measured for TH and QH is provided in Table 10. The step-to-step variations in QH and their statistical significance are listed in Table 11. Figure 8 shows a graphical representation of the raw kinetic measures and their trends, with raincloud plots showing the probability of spread and density of distribution, and box plots showing the central tendency, medians, and quartile ranges.

There was a significant increase of 27.5% ($p$ < 0.001; ES = 2.03) in the maximum vertical force between Steps 1 and 2 of the TH, with a large effect. The maximum vertical force during the QH increased significantly across steps with each ground contact ($p$ < 0.001; $\eta^2_{\text{p}}$ = 0.78). The largest percentage changes were observed between Steps 1 and 2 (22.8%), and similar increases (12.0 - 12.8%) were observed between Steps 2 and 3, and Steps 3 and 4. The distribution of measures of the maximum vertical force increased across each step, with the most extensive spread observed in Step 4 (Figure 8a).

A small but significant increase in the net vertical impulse of 3.5% (p < 0.001; ES = 0.80) between Steps 1 and 2 of the TH. Small increases (7.20%) were observed across Steps 1-4 for net vertical impulse of the QH ($p$ <0.001; $\eta^2_{\text{p}}$ = 0.50). Step-to-step increases ranged from 0.53 to 4.55%, with no change observed between Step 1 and Step 2 (p = 1.000), and a small but significant change in Steps 2-3 (p = 0.04) and Steps 3-4 (p <0.001). There was little change in the mean, median, and data spread across the steps, as shown in Figure 8b.

Significant increases of 98.7% (*p* < 0.001; ES = 1.62) in the vertical braking impulse were observed between Steps 1 and 2 of the TH. Vertical braking impulse increased during QH and differed significantly across steps, the step-to-step changes ranging from 28.1 to 96.8%, with the largest percentage changes seen in the early steps (*p* < 0.001; $\eta^2_p$ = 0.86). A percentage change of 241% was observed between Steps 1 and 4, reflecting the amplified demand for increasing the number of hops in series. The spread in the braking impulse data was similar across the steps, with the largest spread observed in Step 4 (Figure 8c).

The vertical propulsive impulse decreased 23.9% (*p* < 0.001; ES = -1.56) between Steps 1 and 2 of the TH. The vertical propulsive impulse also decreased (15.6 to 21.0%) during the QH (*p* < 0.001; $\eta^2_p$ = 0.87). The spread in the propulsive impulse data was consistent across Steps 1-4 (Figure 8d).

A significant decrease of 57.0% (*p* < 0.001; ES = 1.85) in the net anterior-posterior impulse was seen between Steps 1 and 2 of the TH. Net anterior-posterior impulse also decreased during QH and differed significantly across steps (*p* < 0.001; $\eta^2_p$ = 0.88), with the largest change observed in the final step (%Δ = 128.5%). The net anterior-posterior impulse data distribution was similar across steps, with the largest spread observed in Step 4 (Figure 9a).

**Table 10.** Absolute kinetic data for the TH and QH

| | TH Mean ± SD | QH Mean ± SD |
|---|---|---|
| **Step 1** | | |
| Maximal Vertical Force (N) | 2329 ± 377.1 | 2307 ± 338.2 |
| Net Vertical Impulse (Ns) | 400.1 ± 50.80 | 386.4 ± 50.58 |
| Vertical Braking Impulse (Ns) | 93.80 ± 47.09 | 74.23 ± 41.88 |
| Vertical Propulsive Impulse (Ns) | 308.0 ± 44.12 | 317.3 ± 44.09 |
| Net Anterior-Posterior Impulse (Ns) | 49.87 ± 12.26 | 55.54 ± 11.55 |
| Horizontal Braking Impulse (Ns) | 3.410 ± 1.590 | 2.370 ± 1.360 |
| Horizontal Propulsive Impulse (Ns) | 53.74 ± 11.10 | 58.20 ± 10.97 |
| **Step 2** | | |
| Maximal Vertical Force (N) | 2971 ± 518.6 | 2814 ± 504.4 |
| Net Vertical Impulse (Ns) | 411.4 ± 47.83 | 388.6 ± 51.28 |
| Vertical Braking Impulse (Ns) | 187.0 ± 40.07 | 144.8 ± 32.77 |
| Vertical Propulsive Impulse (Ns) | 236.1 ± 43.34 | 248.4 ± 31.14 |
| Net Anterior-Posterior Impulse (Ns) | 21.46 ± 10.02 | 32.25 ± 6.000 |
| Horizontal Braking Impulse (Ns) | 13.56 ± 4.080 | 8.200 ± 3.010 |
| Horizontal Propulsive Impulse (Ns) | 35.48 ± 8.340 | 41.67 ± 6.560 |
| **Step 3** | | |
| Maximal Vertical Force (N) | | 3150 ± 549.5 |
| Net Vertical Impulse (Ns) | | 393.8 ± 46.22 |
| Vertical Braking Impulse (Ns) | | 194.8 ± 30.51 |
| Vertical Propulsive Impulse (Ns) | | 203.5 ± 32.29 |
| Net Anterior-Posterior Impulse (Ns) | | 13.98 ± 6.890 |
| Horizontal Braking Impulse (Ns) | | 17.90 ± 4.380 |
| Horizontal Propulsive Impulse (Ns) | | 31.67 ± 6.040 |
| **Step 4** | | |
| Maximal Vertical Force (N) | | 3596 ± 710.0 |
| Net Vertical Impulse (Ns) | | 412.4 ± 50.01 |
| Vertical Braking Impulse (Ns) | | 249.3 ± 48.49 |
| Vertical Propulsive Impulse (Ns) | | 172.9 ± 41.27 |
| Net Anterior-Posterior Impulse (Ns) | | -4.790 ± 14.34 |
| Horizontal Braking Impulse (Ns) | | 29.55 ± 8.930 |
| Horizontal Propulsive Impulse (Ns) | | 24.88 ± 7.720 |

**Key:** SD = standard deviation; N = newtons; Ns = newton seconds

Significant increases of 291.8% ($p < 0.001$; ES = -2.22) in the horizontal braking impulse were observed between Steps 1 and 2 of the TH. The horizontal braking impulse also increased (~1160%) during the QH across steps ($p < 0.001$; $\eta^2_p = 0.87$), with significant differences seen between steps and diminishing percentage changes seen across steps (231.2%, 12.0%, 67.0%). The spread in the horizontal braking impulse data gradually dispersed across the steps, with the largest spread observed in Step 4 (Figure 9b).

A significant decrease in horizontal propulsive impulse of 40.0% ($p < 0.001$; ES = -1.60) was observed between Step 1 and 2 of TH. The horizontal propulsive impulse also decreased (57.0%) during QH between steps ($p < 0.001$; $\eta^2_p = 0.84$) with the spread of horizontal propulsive impulse measures greater in Steps 1 and 4 (Figure 9c).

**Table 11.** The marginal means contrasts for each combination of within-subject variables during QH for repeated measures ANOVA

| | Mean Difference (95% CI) | % Δ | *p* | ES |
|---|---|---|---|---|
| **TH Maximal Vertical Force (N)** | | | | |
| Step 2 – Step 1 | 525.76 (359.79 – 691.72) | 22.8 | <0.001 | 1.01 |
| Step 3 – Step 2 | 336.44 (170.48 – 502.40) | 12.0 | 0.001 | 0.64 |
| Step 4 – Step 3 | 403.07 (237.11 – 569.04) | 12.8 | <0.001 | 0.77 |
| **TH Vertical Impulse (Ns)** | | | | |
| Step 2 – Step 1 | 2.057 (-5.513 – 9.627) | 0.53 | 1.000 | 0.05 |
| Step 3 – Step 2 | 7.851 (0.281 – 15.421) | 2.02 | 0.038 | 0.17 |
| Step 4 – Step 3 | 17.917 (10.347 – 25.487) | 4.55 | <0.001 | 0.39 |
| **TH Vertical Braking Impulse (Ns)** | | | | |
| Step 2 – Step 1 | 71.87 (52.99 – 90.75) | 96.8 | <0.001 | 1.89 |
| Step 3 – Step 2 | 52.15 (33.27 – 71.03) | 36.0 | <0.001 | 1.37 |
| Step 4 – Step 3 | 54.79 (35.91 – 73.67) | 28.1 | <0.001 | 1.44 |
| **TH Vertical Propulsive Impulse (Ns)** | | | | |
| Step 2 – Step 1 | -66.65 (-80.87 – -52.42) | 21.0 | <0.001 | -1.84 |
| Step 3 – Step 2 | -46.02 (-60.25 – -31.80) | 18.5 | <0.001 | -1.27 |
| Step 4 – Step 3 | -31.73 (-45.95 – -17.51) | 15.6 | <0.001 | -0.88 |
| **TH Net Anterior-Posterior Impulse (Ns)** | | | | |
| Step 2 – Step 1 | -22.30 (-28.21 – -16.39) | 40.2 | <0.001 | -2.25 |
| Step 3 – Step 2 | -19.26 (-25.17 – -13.35) | 59.7 | <0.001 | -1.94 |
| Step 4 – Step 3 | -17.97 (-23.88 – -12.05) | 128.5 | <0.001 | -1.81 |
| **TH Horizontal Braking Impulse (Ns)** | | | | |
| Step 2 – Step 1 | -5.48 (-8.23 – -2.70) | 231.2 | <0.001 | -1.07 |
| Step 3 – Step 2 | -10.09 (-12.87 – -7.31) | 123.0 | <0.001 | -1.96 |
| Step 4 – Step 3 | -11.99 (-14.77 – -9.21) | 67.0 | <0.001 | -2.33 |
| **TH Horizontal Propulsive Impulse (Ns)** | | | | |
| Step 2 – Step 1 | -16.53 (-20.18 – -12.89) | 28.4 | <0.001 | -2.05 |
| Step 3 – Step 2 | -10.00 (-3.54 – -6.36) | 24.0 | <0.001 | -1.24 |
| Step 4 – Step 3 | -6.79 (-10.43 – -3.14) | 21.4 | <0.001 | -0.84 |

**Key:** CI = confidence interval; N = newtons; Ns = newton seconds; %Δ = percentage change. **Note:** Post-hoc Bonferroni

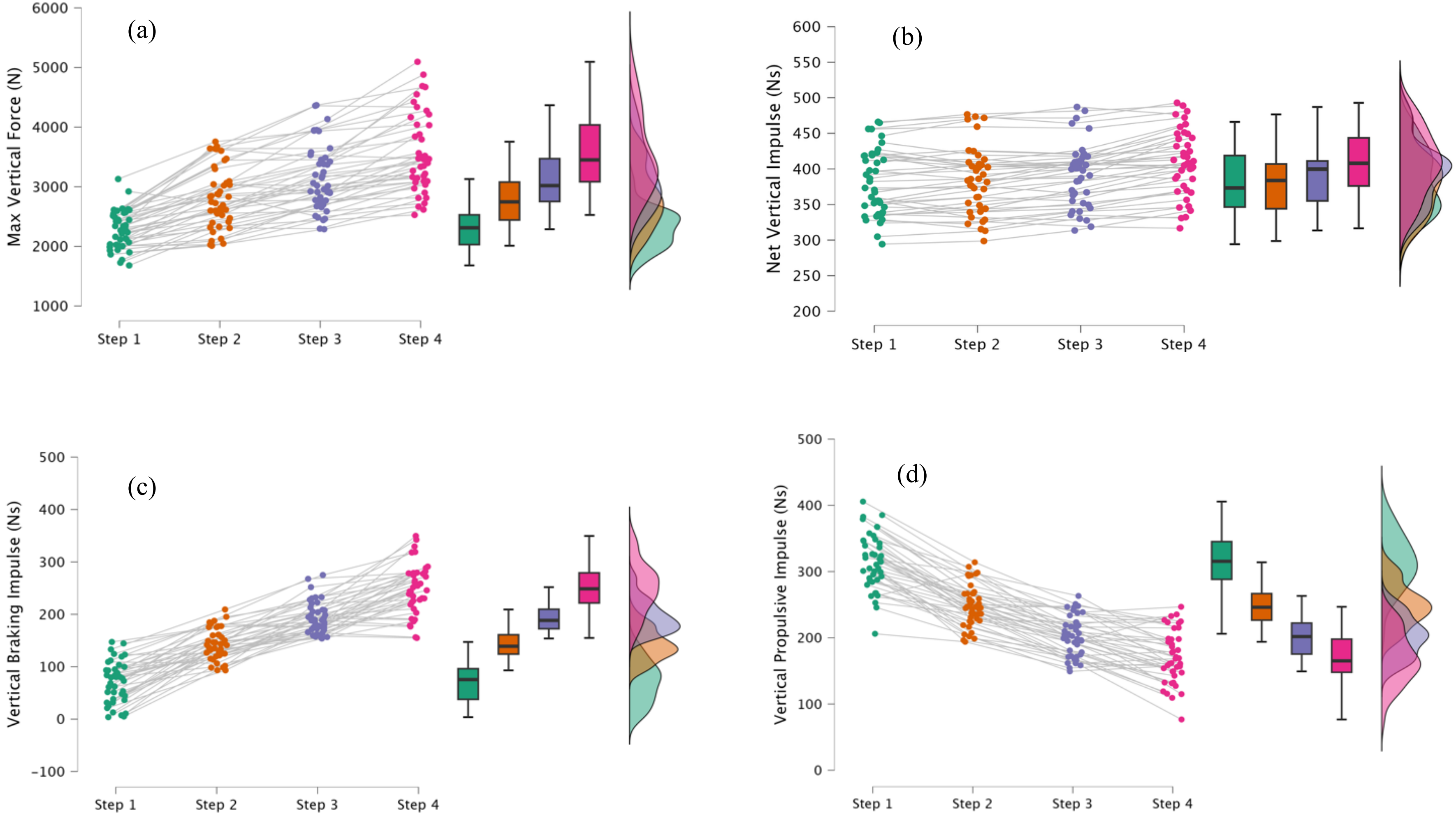


**Figure 8.** Raincloud and boxplots for QH vertical kinetic variables depicting density, spread and measures of central tendency across Steps 1-4

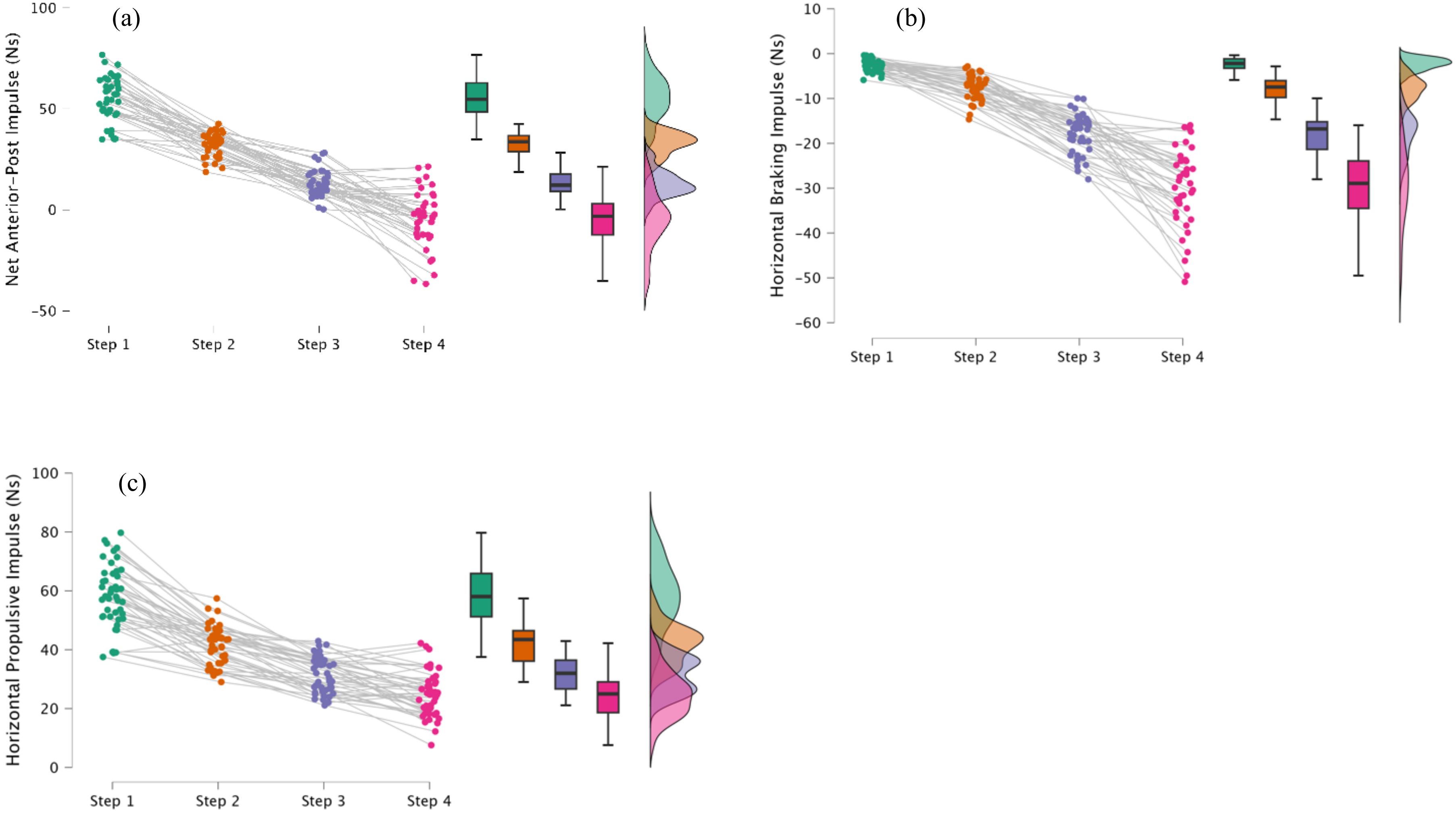


**Figure 9.** Raincloud and boxplots for QH horizontal kinetic variables depicting density, spread and measures of central tendency across Steps 1-4

## 5.4 Discussion and Implications

Whilst the kinematic measures of multiple hops in series have previously been reported [44, 97, 149, 150] and kinetic measures specific to joint work have been quantified [90, 91, 156, 159], to the best of our knowledge, this is the first study in which an extensive summary of kinetic measures for both TH and QH has been reported. Researchers quantifying exercise intensity through mechanical stress have primarily focused on vertically oriented jumping tasks and single-leg standalone jumping movements, using both peak GRF [45, 52, 81, 88] and impulse [45, 52, 81]. Impulse is an important variable, as effective impulse determines the velocity of the CoM. Therefore, the hop distance [110, 133], i.e., the impulse-momentum relationship, is a reliable measure when determining plyometric intensity [81]. As the net vertical and net horizontal (anterior-posterior) impulse measures provide the summed impulses from the braking and propulsive phases, these variables will provide much of the focus of this discussion. They will provide insight into changes in the stretch-load between hops. With this context in mind, this study aimed to quantify the kinetics of both TH and QH, emphasising understanding the increasing stretch-load demands of the QH.

The maximum vertical force across the TH and QH increased from ~2300 N (32 N.kg) to 3600 N (51 N.kg), translating to an average increase of ~14% across successive hops. The vertical braking impulses increased (~75 - 249 Ns), whereas the vertical propulsive impulses decreased (~308 - 172 Ns) across hops. The net effect of these differences was little change (~6%) in net vertical impulse between hops across both jumps, with values ranging from ~386 - 412 Ns. With successive hops, there appears to be an average increase of ~32% in hop vertical braking impulses, indicating a substantial and progressive overload to the tissues responsible for vertical eccentric braking of the downward momentum of the body, namely the plantar-flexor and Vasti groups of the lower limb. The average reduction (~19%) in vertical propulsive impulses across hops and jumps might suggest reduced concentric force production in multiple hops or, most likely, less time to produce that force given the increasing velocity of the CoM.

The horizontal braking impulses increased (~-2 to -30 Ns), whereas horizontal propulsive impulses decreased (~58 to 25 Ns) across hops. The net effect of these differences was a substantial change (~90%) in the net anterior-posterior impulse between hops across both jumps, with values ranging from ~55 to -5 Ns. With successive hops, there appears to be a ~56% average increase in hop horizontal braking impulses, most likely attributed to the greater horizontal and downwards velocities with ensuing hops, but also indicating that the foot during landing is touching down further in front of the line of CoM, most likely due to the system's need to produce greater forces to prevent collapse to the ground.

Of interest was the comparison of demands between the TH and QH and how stretch-load increased with ensuing hops, in agreement with our first hypothesis. Increases in the maximal vertical force and vertical and horizontal braking impulses partly explain this increase in stretch-load. As can be observed in Table 10 and Figure 7 of the QH sequence, the maximum vertical force, which occurs in the initial 'shock' eccentric/stretch phase, steadily increased with successive hops, with the increases between hops on average ~14%. By visual analysis of the vertical (blue) and horizontal (red) increases in braking impulse in tandem with the averaged hop data mentioned previously (increases of ~32 and 56%, respectively). In agreement with our second hypothesis, it can be concluded that the final two hops of the quintuple offer a significantly higher stretch-load than the initial steps in a QH or that of a TH. The addition of further hops in series also resulted in less propulsive demand and greater braking demand, as seen in Figure 10. The subject's ability to maintain or improve performance with increasing hop numbers and an increase in associated vertical forces may be determined by their ability to handle higher system stretch load demands.

These increases in the vertical and horizontal braking impulses are a function of higher forces over shorter ground contact periods. One possible outcome is a change in horizontal braking impulse due to a modified movement strategy in which the subject's heel strikes in front of its CoM, in an attempt to slow down the system. The resultant ‘backwards’ position of the shank and the longer period of ground contact relies on greater muscular force demand of the Vasti group to arrest impact, and the hip extensors to subsequently ‘pull’ the CoM of the subject forwards. Conversely, it is conceivable that coaching the athlete to position the foot under the CoM could reduce the horizontal braking impulse and lend itself to a more positive antero-posterior impulse and greater hop performance, although with increased reliance on a reactive Achilles tendon-calf complex and hip extension torque.

The horizontal braking impulse was highly variable in this group, particularly in Step 4 of QH (see Figure 9), and was most likely attributable to a limited and diminishing stretch-load capacity that could not meet the system's increasing vertical demands. Another possible explanation for this movement variability is that the subject was preparing for the ultimate final leap, as evident in the TH and QH. The position of the heel strike was adjusted in front of the CoM, and the braking focus was increased to assimilate the greatest propulsive impulse and maximise the distance jumped. Future studies could determine this using additional kinematic analyses such as 3-D motion capture.

The magnitude of the increasing stretch-load demand is essential to understand if these jumps are used for assessment and training purposes. For example, competency with TH assessments or training would be a sensible progression prior to using a high-stretch load movement, such as the QH for assessment or training purposes. Figure 11 shows the increase in vertical demand expressed in body weights. In recognition of the rise in force demand with each additional hop, a clinician should acknowledge whether the recovering RTS athlete can manage this level of supra-maximal load and whether they are at risk of injury when progressing from TH and QH training or assessments.

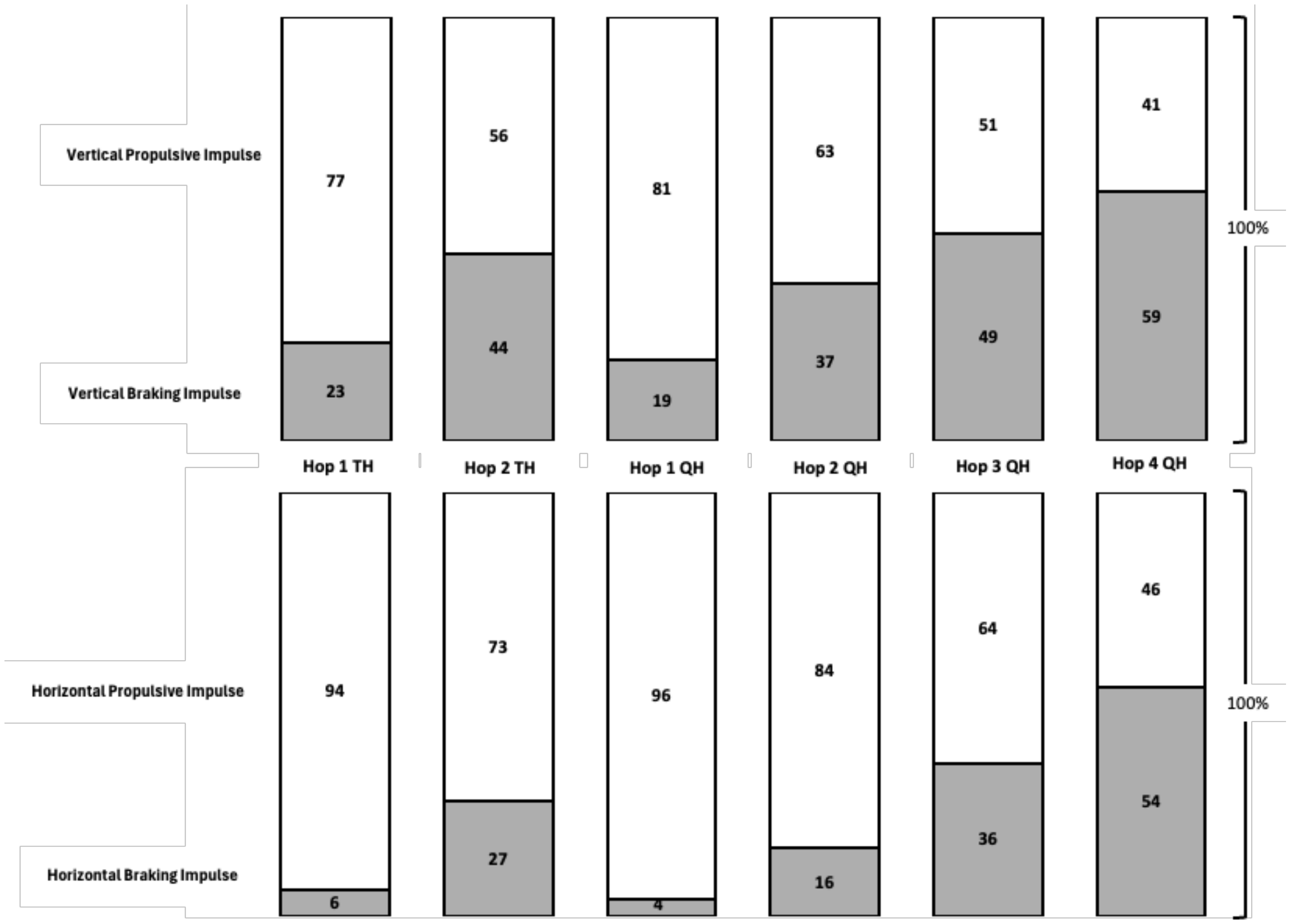


**Figure 10.** Percentage contribution of vertical and braking impulse towards net vertical and anterior-posterior impulse across hops

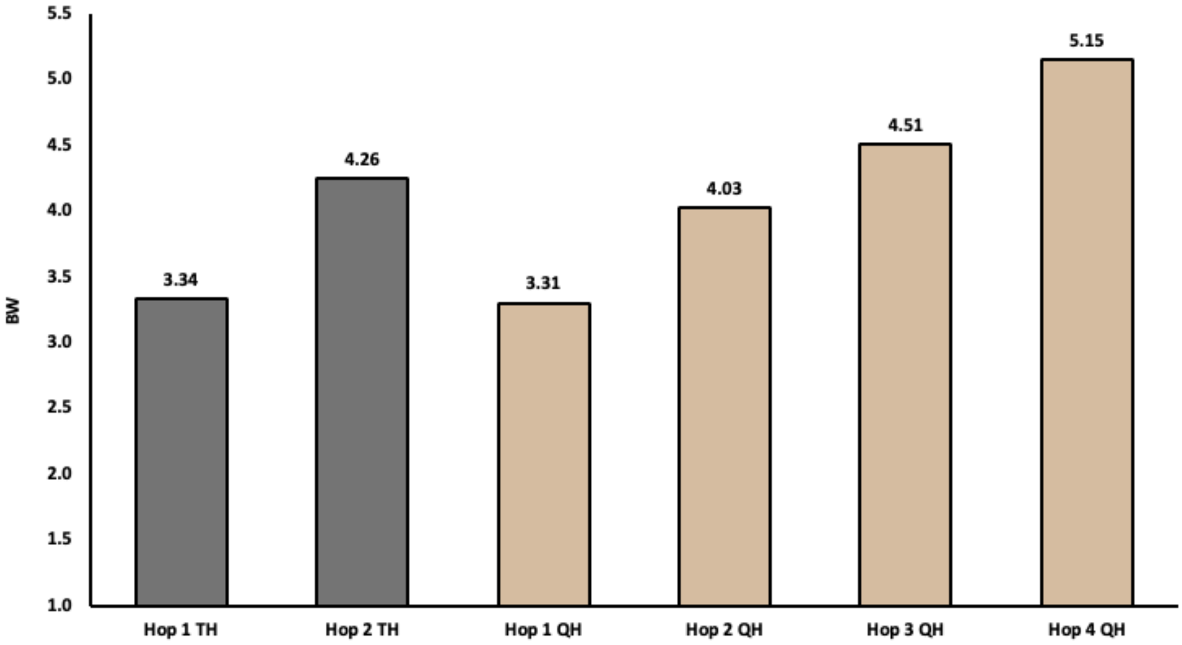


**Figure 11.** Maximal vertical force shown in bodyweights across hops

## 5.5 Summary and Conclusions

Given the scarcity of literature on the kinetic demands of TH and QH and their obvious application in athlete rehabilitation and physical preparation, this study is novel. It provides practitioners with valuable insights into the increasing stretch-load demands of multiple hops in series. When selecting a suitable multiple hop test for rehabilitation or performance, some nuances may distinguish their applications. The significant increases in maximum vertical force and braking impulses across hops differentiate their stretch-load demand; therefore, careful implementation in programming for gradual load tolerance in an athlete in a RTS phase is critical to not overload the lower limb and trunk joints and tissues excessively and injuriously.

The high variability in horizontal braking impulse observed in this study also indicates differences in movement strategies among the groups. While it is recognised that individual movement strategies and physical characteristics both influence optimal performance, which may not be easily de-coupled, an effective coaching strategy to encourage the athlete to position the foot under the CoM could reduce horizontal braking impulse, leading to a more positive anterior-posterior impulse and better hop performance. However, this can only be achieved if the athlete has the physical capacity to handle increased stretch-load demands due to larger vertical forces over shorter periods. Combining kinetic (strengthening) and kinematic (technique cueing) methods will likely produce the best results.

# CHAPTER 6: DO OUTCOME OF MOVEMENT STRATEGY VARIABLES PROVIDE BETTER INSIGHTS INTO ASYMMETRIES DURING MULTIPLE HOPS?

---

This chapter comprises the following paper published in Biomechanics.

**Reference:**

Sharp, A.P., Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Do outcome or movement strategy variables provide better insights into asymmetries during multiple hops? *Biomechanics, 5*(3), 67.

## 6.0 Prelude

In Chapter 5, valuable insights into the increasing stretch-load demands of multiple hops in series was provided. The significant increases in maximum vertical force and braking impulses across hops clearly highlight the stretch-load demands of the latter hops, which has several interesting applications for both strength and conditioning coaches and physiotherapists. Throughout this discussion, a consistent theme emerges: while TH distance offers an easy-to-quantify, reliable, and objective measure of performance for clinicians and coaches, the distance hopped itself is an outcome measure that fails to reveal movement strategies. This inability to distinguish between the movement characteristics of each hop may hide potential deficiencies, such as eccentric braking capacity, which, if undetected, could increase the risk of injury or re-injury. Given this context, the focus of this study was to evaluate how TH and QH kinematics and kinetics can describe vertical and horizontal cyclic asymmetries. Ultimately, clinicians and coaches need diagnostic information that enhances understanding of an individual’s physiological and biomechanical status, enabling better exercise prescriptions to improve patient and athlete outcomes.

## 6.1 Introduction

Acyclic and cyclic jumps are commonly used to assess limb asymmetry, serving as key indicators of injury risk in rehabilitation management and RTS protocols. These jump assessments, conducted with either vertical or horizontal force orientations, offer insights into an individual’s neuromuscular status. When evaluating horizontal asymmetry, the single-leg hop, TH, and crossover-hop are the most commonly used assessments [44, 90, 93, 94, 97, 115, 138]. Davey et al. (2021) [44] concluded that the TH assessments display greater ecological validity for team sport athletes, closely mimicking the propulsive and decelerative force demands associated with short GCT typically observed in these sports. Despite this suggested validity, the reliability measures reported by researchers [115] and their demonstrated application in rehabilitation settings raise concerns that discrete distance values (outcome variables) alone do not adequately capture the nuances of movement strategy [93]. Consequently, Kotsifaki et al. (2022) [93] suggested that a more comprehensive understanding of TH asymmetry could be achieved by integrating outcome variables with those reflecting underlying movement strategies, through kinetic analysis.

Researchers [44, 97, 139] have investigated the usefulness of TH flight times or hop distances divided by GCT, also known as horizontal RSI ($RSI_{hor}$), in quantifying asymmetry. The main findings from these research groups were: (1) TH distance alone masked residual deficits in reactive strength performance; thus, more detailed analyses of individual hop performance may be warranted [97]; (2) although only trivial to small differences in mean asymmetry were observed, significant within-group variation was noted, highlighting the importance of also analysing data individually [44]; (3)

the direction of asymmetry can fluctuate between hops and test sessions, underlining the value of also monitoring the direction of the imbalance [44]; (4) vertical and horizontal RSI shows a poor level of agreement, and when calculating $RSI_{hor}$, flight time and hop distance should not be used interchangeably [138]; and (5) Davey et al. (2021) determined TH $RSI_{hor}$ both within and between sessions to be highly reliable in a group of adolescent male American football players [44].

It is important to note that research on TH asymmetry so far has focused on basic kinematic outcome strategy variables, which have been determined reliable using a simple measuring tape or using basic smartphone video capture [149, 150]. Performance-based outcome variables, such as hop distance, overlook the movement strategies or kinetic demands that contribute to these results. Key elements of movement strategy involve kinetic aspects, such as vertical and horizontal braking and propulsion forces or impulse, that influence kinematic variables like flight time and ground contact duration for each hop [47]. Kinetic variables, such as vertical and horizontal braking and propulsive impulses and forces determined using force platforms, may therefore provide deeper diagnostic insights into cyclic asymmetry and guide more effective exercise prescriptions. Furthermore, Kotsifaki et al. (2021) [89] reported that athletes post-ACLR (anterior cruciate ligament reconstruction) were nearly symmetrical in terms of hop distance (within 3% difference), yet they still displayed moderate to large differences in knee function during propulsion (69%). This is further supported by evidence showing that athletes have returned to sport after rehabilitation but still exhibit significant functional deficits in limb symmetry [74, 85]. Furthermore, the authors of this study have observed that individuals who manage the stretch-load demands of the TH assessments (approximately 3.3 to 4.3 bodyweights) can struggle with the higher stretch-load demands associated with the later landings of the QH assessments (approximately 3.3 to 5.2 bodyweights) [151]. Given the increased stretch-loading in the QH, greater levels of asymmetry may be detectable in the latter hops in those unable to attenuate these increased biomechanical demands. With this information, the primary focus of this paper is to understand the utility of TH and QH kinematics (outcome variables) and kinetics (movement strategy variables) in describing vertical and horizontal cyclic asymmetries. Specifically, the aims were to: 1) determine the magnitude and direction of asymmetries; 2) assess whether kinematic and/or kinetic variables demonstrate greater asymmetry for the same movement; 3) compare vertical and horizontal asymmetries across hops; and 4) evaluate if the magnitude of asymmetry differs between the TH and QH assessments. It was hypothesised that increased asymmetries would be evident in the kinetic measurements of hops that require higher stretch-loads, particularly in the vertical and horizontal braking impulses during hops 3 and 4 of the QH.

## 6.2 Methodology

### 6.2.1 Participants

Forty-four male university athletes (age: 20.1 ± 1.4 years; body mass: 71.2 ± 8.6 kg; height: 171.9 ± 5.1 cm) from a wide range of sports disciplines and expertise from novice to elite; including kendo, baseball, rowing, athletics, windsurfing, cycling, soccer, and basketball volunteered to participate in this study. All subjects were required to be healthy and free from injury at the time of testing. Those with a history of major musculoskeletal injuries (e.g., ruptures or tears of key tendons or ligaments such as the Achilles tendon or ACL were excluded, regardless of rehabilitation status. Ethical approval was obtained from both the Auckland University of Technology Ethics Committee (Reference: 17/133) (Appendix I) and the National Institute of Fitness and Sports in Kanoya Ethics Board (Reference: 8-123) (Appendix II) and study procedures adhered to the Declaration of Helsinki. All subjects provided written informed consent (Appendices IV and V). Body mass was measured to the nearest 0.1 kg, and height was assessed using standard protocols from the International Society for the Advancement of Kinanthropometry [123], using a digital scale and stadiometer (Tanita DC-217A, Tokyo, Japan).

### 6.2.2 Procedures

Subjects completed a familiarisation session at least three days prior to testing. This included a standardised warm-up protocol, approximately 20 min in length, which was repeated on the day of testing. The time of testing varied between a morning or afternoon session; however, ambient temperature was consistent at 10 - 12 degrees centigrade in an indoor training facility. The warm-up involved dynamic stretching exercises for both upper and lower limbs, general movement to increase body temperature, explosive bounding drills to replicate the demands of the tests, and progressively faster 30 m sprints. Testing began five minutes after the warm-up.

The TH and QH consisted of three and five consecutive horizontal hops, respectively, performed on the same leg (Figure 12). The reliability of these tests has been determined previously [149, 150]. Due to the high physical demands of these tests, subjects completed three trials of the TH and two trials of the QH in a randomised order for both DOM and NDOM limbs. In this study, dominance was determined by their 'kicking limb', as has been determined and commonplace in other similar studies [48]. A 2 min rest period was provided between trials and before switching legs to reduce fatigue and injury risk. Each trial began with the participant balancing on one leg before initiating the hops. After the final hop, subjects were instructed to land on both feet. Touching the ground with the hands was permitted, provided the hopping foot did not advance after landing. This approach encouraged maximal horizontal distance. Arm movement was allowed to reflect natural athletic coordination. Subjects were instructed to "cover the greatest horizontal distance in the shortest amount of time."

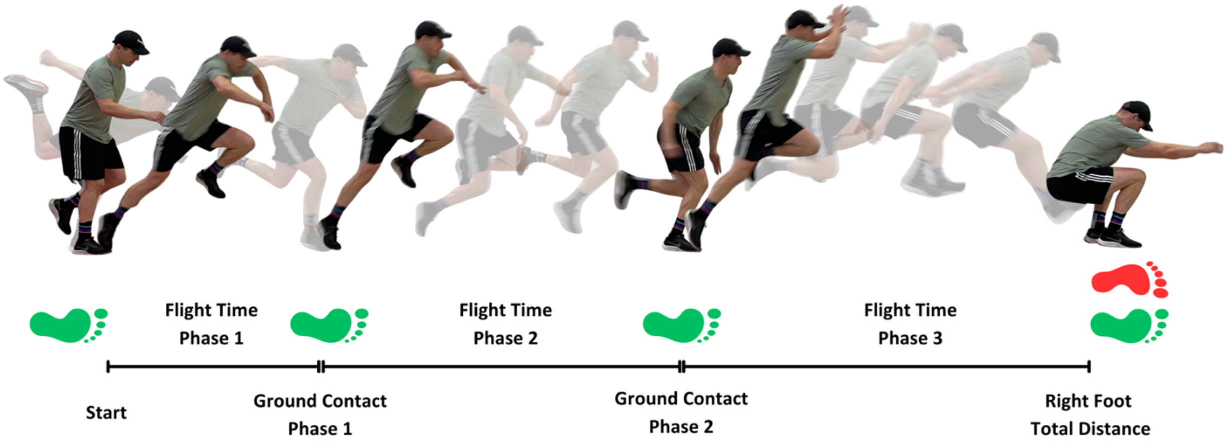


**Figure 12.** The sequence of a right foot TH test (green)

All hop trials were performed on an indoor synthetic track surface (Hasegawa Sports Facilities, Tokyo, Japan), which housed a series of 54x embedded force platforms (TF-90100, TF-3055, TF-32120; Tec Gihan, Kyoto, Japan). These platforms were connected to a single computer system for synchronised data acquisition. GRFs were recorded at a sampling rate of 1000 Hz for each trial.

The force data was captured, exported, tagged, and stored for subsequent analysis. GRF signals were processed using a 4th-order Butterworth low-pass digital filter with a 50 Hz cutoff frequency to remove any mechanical or electrical 'noise' from the force platform itself. From these filtered data, both horizontal and vertical components of propulsive and braking kinetics were extracted. Impulses were calculated by integrating the GRF signals over the appropriate time intervals.

Vertical braking impulse was defined as the period from the moment of initial heel strike to the point where the CoP crosses the zero axis at the anterior-posterior transition, assuming that the subject's CoM was directly above the foot at this point, as previously described [114, 118]. This classification was internally validated with high consistency using a MAC3-D motion capture system (Motion Analysis Corp., Santa Rosa, CA, USA; 250 Hz) to determine agreement between the instance of the participant's centre of gravity and maximal knee flexion, with the instance of a switch from horizontal braking to horizontal propulsive force and the second peak of the vertical GRF. Both vertical and horizontal braking impulses were determined as the time integration of the GRF during the same period, from the moment of the initial heel strike until the moment the force time curve crosses the zero axis in the anterior-posterior waveform. All kinetic variables were normalised to body mass to account for inter-individual variability. Data processing and analysis were conducted using a custom MATLAB algorithm (R2021a, MathWorks Inc., Natick, MA, USA).

### 6.2.3 Data Processing and Outcome Measures

Touchdown and take-off were identified using a 20 N threshold in the vertical GRF from the filtered data. The $RSI_{hor}$ was calculated for each individual hop as described by Sarabon et al. [138], as the ratio between hop distance by the preceding ground contact time (Equation 6). Total $RSI_{hor}$ for each trial was computed by dividing the total hop distance by the cumulative ground contact time across all hops.

$$Reactive\ Strength\ Index\ Horizontal\ (RSI_{hor}) = \left(\frac{\boldsymbol{Hop\ Distance}}{\boldsymbol{Ground\ Contact\ Time}}\right)$$

**Equation 6.** Reactive strength index horizontal

### 6.2.4 Statistical Analysis

Descriptive statistics, including means and standard deviations, were used to summarise central tendency and variability. Assumptions of univariate normality, outliers, and sphericity were assessed prior to inferential analysis. Outliers were identified through boxplot inspection, with data points exceeding three standard deviations from the mean manually excluded from further analysis. The Shapiro–Wilk test [144] was used to assess normality, complemented by Q–Q plot inspection for visual evaluation of kurtosis and skewness. Limb asymmetry between DOM and NDOM limbs was calculated using average trial data in Microsoft Excel (version 16.93.1; Microsoft Corp., Washington, USA) following Equation 7 [17, 44]. The magnitude of asymmetry was expressed as a percentage by comparing the mean values of the DOM and NDOM limbs. Paired *t*-tests were used to determine the statistical significance of these differences.

$$Asymmetry\ = \left[\left(\frac{100}{Maximum\ Value}\right) \times\ \ (Minimum\ Value)\right] \times -1 + 100$$

**Equation 7.** Hop asymmetry percentage (%)

The direction of individual asymmetries was determined by using an IF function (*IF(DOM limb/NDOM limb, -1, 1)) as described by Davey et al. (2021) and used for further individual analysis [44].

## 6.3 Results

The means and standard deviations for all kinematic and kinetic data are detailed in supplementary Tables S1 and S2 (Appendix VII). Asymmetries in kinematic data for the TH and QH protocols are summarized in Table 12. The average kinematic asymmetries were consistently below 7.1%, ranging from 0.00% to 28.9%, with RSI showing the greatest asymmetry. Large standard deviations were observed across all asymmetries, indicating high variability. The magnitude of these asymmetries varied across different kinematic parameters. Notably, greater flight times (0.629 to 1.81%) were observed in the NDOM limb during all QH trials, contributing to longer hop durations for the NDOM limb. However, across the forty kinematic variables, significant differences between limbs of averaged values were only seen in Flight Time (Hop 3) and Hop Time (Hop 2-3) ($p < 0.05$) of TH which are both closely linked (Appendix VII - Table S1). Averaged kinetic asymmetries ranged from 0.0% to 95.4%, with the largest asymmetries observed in the vertical and horizontal braking impulses and are summarised in Table 13. The magnitude of asymmetry in the kinetic variables varied across the TH steps. During the QH test, greater (31.5-51.8 N.kg) mean maximal vertical force values were consistently observed in the NDOM limb across steps compared to the DOM limb (31.2-50.1 N.kg), whereas larger (0.833-0.370 Ns.kg) horizontal propulsive impulses were consistently observed in the DOM limb across all hops compared to the NDOM limb (0.814-0.313 Ns.kg) across steps. Vertical braking impulses for both the TH and QH protocols were significantly greater for Hop 1 than subsequent hops (TH: 29.6 ± 24.1%; QH: 39.8 ± 31.6%). The asymmetry between hops decreased by ~2% across subsequent hops, with reduced between-subject variability (11.2% to 15.6%, range: 0.0% to 53.8%). Vertical propulsive impulse asymmetries were consistent across the TH and QH protocols (7.77% to 15.4%, range = 0.0% to 61.6%), with minimal changes in asymmetry between hops (~1% to 2%). Notably, significantly greater variability was observed in the final hop for both the TH and QH protocols, inflating the mean values (TH range: 0.0% to 47.5%; QH range: 0.75% to 61.6%) when compared to earlier hops (range: 0.0% to 31.0%). Horizontal braking impulse asymmetries decreased between each hop for the TH and QH protocols (38.8% to 19.9%), with a reduction in between-subject variability (range: 0.0% to 90.9%). A ~14% Δ in asymmetry was observed between Hops 1-2 and Hops 2-3 in the TH protocol, and a ~4% to 11% Δ was noted between hops in the QH protocol. In contrast, horizontal propulsive impulse asymmetries increased between hops for both protocols (10.4% to 17.6%). A ~44% Δ in asymmetry was observed between Hops 1-2 and Hops 2-3 in the TH protocol, while the Δ in asymmetry between hops in the QH protocol ranged from ~1% to 3%. Significant differences between limbs were only seen in horizontal propulsive impulse (Hops 2-3) of the TH ($p < 0.001$) and Hops 3-4 and Hops 4-5 in the QH ($p < 0.05$).

**Table 12.** TH and QH mean asymmetry scores (%) ± SD for hop kinematics

| | **TH** | | **QH** | |
|---|---|---|---|---|
| **Asymmetry Variable** | **Means ± SD (%)** | **Range (%)** | **Means ± SD (%)** | **Range (%)** |
| **Flight Time** | | | | |
| Hop 1 | 4.72 ± 3.85 | 0.00 to 14.3 | 4.63 ± 3.23 | 0.00 to 12.9 |
| Hop 2 | 4.51 ± 3.38 | 0.00 to 11.8 | 6.31 ± 5.94 | 0.00 to 26.5 |
| Hop 3 | 4.59 ± 3.92 | 0.00 to 14.0 | 6.18 ± 4.26 | 0.00 to 17.1 |
| Hop 4 | | | 5.24 ± 3.98 | 0.00 to 17.1 |
| Hop 5 | | | 4.34 ± 3.64 | 0.00 to 14.9 |
| **Ground Contact Time** | | | | |
| Hops 1-2 | 5.41 ± 3.92 | 0.00 to 16.7 | 4.77 ± 4.02 | 0.00 to 17.2 |
| Hops 2-3 | 5.25 ± 3.41 | 0.00 to 14.3 | 5.09 ± 4.02 | 0.00 to 16.7 |
| Hops 3-4 | | | 5.52 ± 4.42 | 0.00 to 17.9 |
| Hops 4-5 | | | 4.58 ± 3.66 | 0.00 to 14.3 |
| **Hops Times** | | | | |
| Hops 1-2 | 3.41 ± 3.14 | 0.00 to 12.3 | 4.52 ± 2.95 | 0.00 to 11.3 |
| Hops 2-3 | 3.49 ± 2.24 | 0.00 to 9.23 | 4.25 ± 2.79 | 0.00 to 10.5 |
| Hop 3-4 | | | 3.83 ± 3.44 | 0.00 to 12.3 |
| Hop 4-5 | | | 3.48 ± 2.75 | 0.00 to 13.0 |
| Total Hop Time | 2.39 ± 2.18 | 0.00 to 9.20 | 2.45 ± 1.62 | 0.00 to 6.29 |
| **Hop Distance** | | | | |
| Hop 1 | 3.67 ± 2.54 | 0.00 to 11.2 | 3.66 ± 3.27 | 0.00 to 12.6 |
| Hop 2 | 3.04 ± 2.41 | 0.00 to 9.41 | 3.50 ± 3.16 | 0.00 to 12.7 |
| Hop 3 | 3.18 ± 2.38 | 0.00 to 11.1 | 3.88 ± 2.35 | 0.40 to 10.1 |
| Hop 4 | | | 4.01 ± 3.07 | 0.50 to 10.4 |
| Hop 5 | | | 4.65 ± 3.19 | 0.00 to 11.9 |
| Total Hop Distance | 2.39 ± 1.89 | 0.18 to 10.6 | 3.32 ± 2.72 | 0.09 to 9.34 |
| **Reactive Strength Index** | | | | |
| Hops 1-2 | 5.45 ± 4.05 | 0.14 to 22.0 | 5.49 ± 4.86 | 0.00 to 25.8 |
| Hops 2-3 | 6.26 ± 4.59 | 0.25 to 17.0 | 6.08 ± 5.92 | 0.13 to 28.9 |
| Hops 3-4 | | | 7.07 ± 5.29 | 0.13 to 25.4 |
| Hops 4-5 | | | 7.04 ± 4.56 | 0.33 to 18.5 |
| Total $\text{RSI}_{\text{hor}}$ | 4.87 ± 3.33 | 0.27 to 14.2 | 5.16 ± 4.29 | 0.08 to 20.5 |

**Key:** SD = Standard Deviation; Time variables = seconds; Distance variables = meters; RSI = m.s$^{-1}$

**Table 13.** TH and QH mean asymmetry scores (%) ± SD for hop kinetics

| | TH | | QH | |
|---|---|---|---|---|
| **Asymmetry Variable** | **Means ± SD (%)** | **Range (%)** | **Means ± SD (%)** | **Range (%)** |
| **Maximal Vertical Force** | | | | |
| Hops 1-2 | 9.94 ± 7.87 | 0.15 – 33.9 | 8.06 ± 7.24 | 0.33 – 30.6 |
| Hops 2-3 | 10.3 ± 7.53 | 0.07 – 29.1 | 10.4 ± 8.88 | 0.08 – 36.6 |
| Hops 3-4 | | | 11.2 ± 8.70 | 0.96 – 28.3 |
| Hops 4-5 | | | 11.5 ± 7.61 | 0.41 – 29.1 |
| **Vertical Braking Impulse** | | | | |
| Hops 1-2 | 29.6 ± 24.1 | 0.00 – 91.2 | 39.8 ± 31.6 | 0.00 – 95.4 |
| Hops 2-3 | 14.3 ± 12.0 | 0.75 – 51.1 | 15.6 ± 12.4 | 0.78 – 53.8 |
| Hops 3-4 | | | 13.5 ± 10.9 | 0.33 – 40.2 |
| Hops 4-5 | | | 11.2 ± 8.96 | 0.00 – 30.8 |
| **Vertical Propulsive Impulse** | | | | |
| Hops 1-2 | 7.77 ± 5.95 | 0.45 – 25.6 | 8.93 ± 6.13 | 0.46 – 27.6 |
| Hops 2-3 | 9.44 ± 8.87 | 0.00 – 47.5 | 7.96 ± 5.44 | 0.00 – 24.3 |
| Hops 3-4 | | | 10.2 ± 7.15 | 0.32 – 31.0 |
| Hops 4-5 | | | 15.4 ± 14.0 | 0.75 – 61.6 |
| **Horizontal Braking Impulse** | | | | |
| Hops 1-2 | 38.8 ± 26.0 | 0.00 – 90.9 | 32.4 ± 23.6 | 0.00 – 87.5 |
| Hops 2-3 | 24.9 ± 16.6 | 0.00 – 72.7 | 36.9 ± 23.6 | 0.00 – 84.0 |
| Hops 3-4 | | | 25.0 ± 14.2 | 0.00 – 61.3 |
| Hops 4-5 | | | 19.9 ± 15.0 | 1.72 – 51.8 |
| **Horizontal Propulsive Impulse** | | | | |
| Hops 1-2 | 10.8 ± 7.07 | 0.00 – 28.4 | 10.4 ± 8.91 | 0.00 – 37.4 |
| Hops 2-3 | 14.8 ± 9.30 | 0.00 – 34.0 | 11.8 ± 8.44 | 0.00 – 31.7 |
| Hops 3-4 | | | 14.4 ± 9.82 | 0.00 – 42.2 |
| Hops 4-5 | | | 17.6 ± 12.3 | 2.56 – 66.7 |

**Key:** SD = Standard Deviation; Force variables = N; Impulse variables = Ns.kg

An individualised analysis of QH asymmetry, including both magnitude and direction, is presented in Table 14. Three subjects were selected based on their hop performance, representing the furthest, mean, and shortest QH distances, respectively. While no consistent trend was observed in the direction of kinematic measures across the subjects, ground contact time and hop distance demonstrated limb-specific biases in subjects 2 and 3. Specifically, subject 2 exhibited a bias toward the DOM limb, whereas subject 3 showed a bias for the NDOM limb. Kinetic measures did not reveal a consistent trend in limb dominance across subjects. However, subject 2 exhibited a dominant limb bias in both vertical braking and horizontal propulsive forces across the hops.

**Table 14.** QH asymmetry direction within individuals of varying QH success

| | **Subject 1** | **Subject 2** | **Subject 3** |
|---|---|---|---|
| **QH Distance** (DOM/NDOM/mean) | 14.1m/14.1m/14.1 m | 11.3m/10.8m/11.1m | 7.80m/8.15m/7.97m |
| **Variable** | **Asymmetry/Direction** | **Asymmetry/Direction** | **Asymmetry/Direction** |
| **Hop Distance** | | | |
| Hop 1 | 1.51%/NDOM | 3.80%/DOM | 7.30%/NDOM |
| Hop 2 | 1.92%/DOM | 4.81%/DOM | 3.50%/NDOM |
| Hop 3 | 1.40%/NDOM | 4.80%/DOM | 3.23%/NDOM |
| Hop 4 | 1.67%/DOM | 2.08%/DOM | 7.00%/NDOM |
| Hop 5 | 0.27%/DOM | 4.44%/DOM | 0.97%/NDOM |
| Total Hop Distance | 0.21%/DOM | 3.29%/DOM | 4.29%/NDOM |
| **Ground Contact Time** | | | |
| Hops 1-2 | 3.85%/DOM | 6.67%/DOM | 9.68%/NDOM |
| Hops 2-3 | 16.7%/DOM | 3.45%/DOM | 0.00%/n/a |
| Hops 3-4 | 4.35%/NDOM | 7.14%/DOM | 7.41%/NDOM |
| Hops 4-5 | 4.76%/NDOM | 0.00%/n/a | 10.7%/NDOM |
| **Vertical Braking Impulse** | | | |
| Hops 1-2 | 57.0%/NDOM | 90.9%/DOM | 34.2%/DOM |
| Hops 2-3 | 16.6%/DOM | 9.41%/DOM | 42.3%/DOM |
| Hops 3-4 | 18.4%/NDOM | 0.37%/DOM | 31.7%/NDOM |
| Hops 4-5 | 22.8%/ DOM | 0.30%/DOM | 28.3%/NDOM |
| **Horizontal Braking Impulse** | | | |
| Hops 1-2 | 0.00%/n/a | 0.00%/NDOM | 77.8%/NDOM |
| Hops 2-3 | 80%/NDOM | 7.69%/NDOM | 50.0%/DOM |
| Hops 3-4 | 56.5%/NDOM | 20.00%/DOM | 25.0%/DOM |
| Hops 4-5 | 46.0%/NDOM | 2.44%/DOM | 29.0%/NDOM |
| **Vertical Propulsive Impulse** | | | |
| Hops 1-2 | 11.2%/DOM | 0.78%/NDOM | 99.6%/NDOM |
| Hops 2-3 | 1.78%/NDOM | 0.00%/n/a | 43.4%/NDOM |
| Hops 3-4 | 9.30%/DOM | 2.29%/DOM | 44.4%/DOM |
| Hops 4-5 | 25.6%/DOM | 1.53%/DOM | 49.1%/DOM |
| **Horizontal Propulsive Impulse** | | | |
| Hops 1-2 | 7.34%/DOM | 2.13%/DOM | 15.4%/DOM |
| Hops 2-3 | 5.19 %/NDOM | 14.3%/DOM | 5.66 %/NDOM |
| Hops 3-4 | 15.2%/DOM | 12.8%/DOM | 18.8%/NDOM |
| Hops 4-5 | 28.3%/DOM | 21.1%/DOM | 6.25%/DOM |

**Key:** QH = quintuple hop; m = metres; NDOM = non-dominant; DOM = dominant

## 6.4 Discussion

Physiotherapists and strength and conditioning coaches commonly utilise multiple hop movements to assess limb asymmetry, which serves as a key indicator of injury risk and plays an essential role in rehabilitation and RTS protocols. This research aimed to enhance the understanding of how TH and QH, and their associated asymmetries, could be used effectively in clinical and performance settings. Specifically, the aims were to: 1) determine the magnitude and direction of asymmetry; 2) whether kinematic and or kinetic variables were more sensitive to asymmetries; 3) whether vertical and horizontal asymmetries were comparable across hops; and 4) if the magnitude of asymmetry differed if a TH or QH was used. The main findings were as follows: 1) the averaged kinematic asymmetries were below 7.1%, and ranged from 0.00% to 28.9%, with the greatest asymmetries observed in the QH (hop 2-3) RSI, and individual asymmetries showed no consistent trend across variables, however ground contact time and hop distance showed limb-specific biases in two of the three subjects; 2) the average kinetic asymmetries were under 39.8%, ranging from 0.00% to 95.4%, with the largest asymmetries found in vertical braking impulse (hop 1-2); 3) greater asymmetries were noted in braking (mean 14.3-38.8%, max 95.4%) rather than propulsive (mean 7.77-14.8%, max 66.7%) impulses, however there was no evidence for an increase in asymmetry with greater stretch loads (i.e. hops 3-4) as hypothesized; and, 4) there was a great deal of individual variability across measures as evidenced by large ranges and standard deviations.

A primary aim of the study was to determine the magnitude of asymmetry in both the kinematics and kinetics of horizontal multiple hops in series, specifically GRFs on embedded force platforms. Our findings were that average measures of kinematic asymmetry were < 7.1% for both the TH and QH assessments, which were in agreement with previously reported kinematic asymmetries [44] as well as less than asymmetry thresholds (10-15%) thought to affect performance or increase injury prevalence [20]. Davey et al. (2021) [44] reported mean asymmetries in kinematic variables of TH assessment ranging from 3.73 to 7.79% which aligned closely with our findings (2.39 to 5.25%). Whilst the RSI are not directly comparable given different computations (flight time vs. hop distance), the increases in RSI asymmetry observed by Davey et al. (2021) [44] between TH (~7.4 to 11.0%), were not reflected in our results (~5.5 to 6.3%), or for the QH assessment (~5.5 to 7.0%). The average kinetic asymmetries were substantially greater (< 38.8%) than the kinematic asymmetries, with measures reaching as high as 95.4% observed in braking impulse variables. This is likely due to the variability associated with braking movement strategies and/or eccentric force capability [78], along with instantaneous fluctuations in mass-specific impulse. The direction of asymmetries observed for both kinetic and kinematic variables was non-uniform and consistent with previously reported studies [17-19, 44, 97], and individual analysis of both kinematic and kinetic data is justified.

Of interest to the authors was the magnitude of asymmetry associated with kinematic or kinetic variables. As intimated previously, kinetic variables are more sensitive to quantifying movement asymmetry, given that the averaged kinematic asymmetries were below 7.1% (ranging from 0.00% to 28.9%), whereas averaged kinetic asymmetries for TH and QH were as high as 38.8% (ranging from 0.00% to 95.4%). Similar kinetic asymmetries have been noted previously in horizontally oriented single-leg jump tasks. Bishop et al. (2021) noted individual asymmetries in peak force (~28%), eccentric impulse (~34%), and concentric impulse (~22%) for single-leg broad jumps [17]; however, not to the magnitude of those seen in this study, which makes sense given the higher stretch-loading associated with multiple hops and in particular the fourth and fifth hops of a QH assessment [151]. Our findings support the work of Kotsifaki et al (2021) who suggested that reporting the asymmetry associated with discrete outcome variables such as distance jumped does not adequately characterise the quality of the movement, and that movement strategy (kinetic) variables should be considered as they can give a fuller picture of hip-knee-ankle function in making decisions on RTS [89].

Additionally, it was of interest whether horizontal and vertical kinetic asymmetries were comparable across hops. When examining propulsive impulses, asymmetries were relatively similar between hops, with horizontal asymmetries being ~2-5% greater than vertical propulsive asymmetries, with this difference increasing with each successive hop. In contrast, horizontal braking impulses, except Hops 1-2, were ~10-20% greater than their vertical counterparts. To the authors' knowledge, no other researchers have examined asymmetries in this manner. Whether these differences can be explained in terms of physical or technical deficiencies is unknown; however, it may be that horizontal eccentric/braking capability was relatively untrained in this cohort. Alternatively, the effect of foot placement relative to the moving CoM could have influenced braking forces more than vertical braking impulses. Interestingly, Kotsifaki et al (2021) found that TH asymmetry in a cohort recovering from ACLR was more pronounced in the force generation/concentric phase rather than the force absorption/eccentric phase, which was not the case in this study; the physiological status of the respective cohorts no doubt explaining the differences [89]. Furthermore, Lloyd et al. (2020) concluded that TH distance masked the residual deficits in reactive strength performance, and our vertical and horizontal braking asymmetries certainly support such a contention [97].

It was hypothesised that the increased stretch-load demand of QH assessment would result in more significant asymmetries in the later hops. Regarding vertical and horizontal propulsive impulse, the actual asymmetry increased by ~7% across jumps. However, contrary to the hypothesis, no significant increase in asymmetries were observed with greater stretch loads (i.e., hops 3-4); in fact vertical and horizontal braking impulse asymmetry decreased by ~13 to 28% across hops, and therefore the hypothesis was rejected. Why this is the case is unclear, and since no other research group has examined the effect of stretch-loading asymmetry, comparing our findings is problematic.

It is important to note the large standard deviations observed with some of the averaged asymmetry measurements, highlighting considerable within and intra-subject variability, underlying the importance of looking past the averaged data and more at individual results; this variability has been reported in previous studies [17, 44, 97]. The levels of variability seen in this study are incomparable to those seen in other multiple hop studies, a phenomenon with this type of testing. Asymmetries higher than 95% were seen in braking impulses, and only comparable to those seen in kinetics of high velocity sprinting, but incidentally not statistically significant due to the high variability seen [55]. Previously, Bishop et al. (2022) [18] determined that the magnitudes of asymmetry were inconsistent across time points during a competition season; however, they also determined that limb dominance was consistent. It is conceivable that substantial shifts in limb dominance and magnitude are expected, within sessions and over time. The variability in movement strategy, both for propulsion and braking, mainly depends on the preceding hop strategy and is not independent of one another. Therefore, dominance could be influenced by, and frequently change based on, the variable being assessed and the task in question [48]. Regardless, this high variability likely precludes any meaningful between-group session comparisons, and our results would support other authors' suggestions to analyse symmetry data individually [97].

A limitation to this study was the utilisation of a heterogeneous non-injured sample of male university-level athletes; therefore, generalisations of these results to other populations, such as females or those with lower limb injuries, must be made cautiously.  Whilst every reasonable precaution was taken to ensure subjects were in a similar state of rest from physical training, this could not be guaranteed due to the varied nature of the sports involved. However, other researchers have suggested that this may not impact the magnitude and direction of asymmetry [18, 44]. Further to this is the determination of dominance between limbs for limb-to-limb comparisons. In this study, dominance was determined by their ‘kicking limb’, whilst this might be a rational approach and commonplace in other studies [48], this does not establish it as a ‘stronger limb’, or a better performing limb in hopping or other sports-related tasks [49], as this is highly individual. Further, there is the potential for this to further mask asymmetry due to quantification of dominance. In contrast, studies in injured cohorts have used affected or injury limb versus non-affected or uninjured limb in their classification [74, 93, 97].

## 6.5 Conclusions and Practical Applications

This study advances the understanding of the expected magnitude of asymmetries that can be observed in horizontally oriented hopping tasks by highlighting understanding of the potential asymmetries in outcome (kinematic) and movement strategies (kinetic) factors influencing hop performance. Consistent with previously reported perspectives, the authors suggest that multiple hop tasks, such as the TH and QH, provide a more functionally relevant assessment of lower limb musculature and asymmetries than single hop variations, and that performance coaches utilise these assessments to provide greater insight into training recommendations. While hop distance is commonly used as a reliable outcome-based measure, it offers limited insight into the underlying movement strategies employed during task execution and an understanding of movement strategy could provide practitioners in rehabilitative settings with an objective understanding of potential future injury risk and drive RTS milestones. This limitation may obscure key deficits, such as reduced eccentric braking capacity that could elevate the risk of injury or re-injury if left unidentified.

To enhance diagnostic utility, practitioners are encouraged to clearly differentiate between outcome measures and movement strategy variables, and where feasible, to assess both concurrently. Particular attention should be given to distinguishing propulsive and braking mechanisms, as well as parsing horizontal and vertical components of motion. Although averaged data can reveal general trends, a more individualised approach is recommended to capture limb asymmetry and movement strategies in more detail. Furthermore, given the minimal differences in asymmetry identified between TH and QH tests, the inclusion of both in assessment batteries may be unnecessary. Notably, technologies other than force platforms, such as mobile video analysis or inertial sensors, can yield valuable information in movement strategies in more accessible and cost-effective ways. Furthermore, future research should consider longitudinal studies in populations returning to play and those under fatigue.

# CHAPTER 7: USING MULTIPLE HOP ASSESSMENTS AND REACTIVE STRENGTH INDICES TO DIFFERENTIATE SPRINTING PERFORMANCE IN SPORTSMEN

This chapter comprises the following paper published in Applied Sciences.

**Reference:**

Sharp, A.P., Neville, J., Nagahara, R., Wada, T. & Cronin, J.B. (2025). Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen. *Applied Sciences, 15*(4), 1685.

## 7.0 Prelude

A recurring theme throughout the chapters has been to assess whether the QH test offers any advanced diagnostic information beyond the TH test. This has been examined in terms of kinematics, kinetics, and asymmetries within the thesis, as well as in performance and rehabilitation contexts. From the beginning, the usefulness of hop assessments for profiling, monitoring, and training sprint performance was of particular interest. The TH is widely used by practitioners focusing on the neuromuscular function of athletes during rehabilitation and sports performance. The QH is less extensively researched, possibly due to the greater neuromuscular demands of the latter hops. In Chapter 6, increases of approximately 56% in maximal vertical force, 236% in vertical braking impulse, and 1147% in horizontal braking impulse across steps were observed. Given the higher neuromuscular demands, the QH may serve as a better discriminator of sprint ability compared to the TH. Whether this is true was the main focus of this chapter. The results should provide practitioners with valuable insights into the potential usefulness of multiple hop tests for evaluating and improving athletic performance.

## 7.1 Introduction

Multiple hops and jumps, specifically TH and QH, have been found to be valid and reliable tools for evaluating athletes’ physical capabilities [23, 69, 115, 149, 150]. Moreover, these types of hop and stop tests are considered suitable for late-stage rehabilitation assessment and for improving athletic performance, such as sprinting, as their execution requires high neuromuscular demands, and in turn necessitates a significant tolerance for stretch-load through cyclical expressions of unilateral propulsive and braking forces [161]. Four research groups [33, 68, 103, 104] have examined the relationship between TH distance and short (10 - 20 m) sprint performances (times and velocities), with some variability observed between these studies ($r$ = 0.33 to −0.89). A very large negative correlation ($r$ = −0.86) between TH distance and 20 m sprint time was reported in recreationally engaged male sports athletes [103], and strong correlations ($r$ = 0.68) with 10-yard sprint time, again in a cohort of mixed sub-elite level male athletes [33]. Habibi et al. observed similarly high correlations ($r$ = 0.89) for sub-elite male sprinters with 10 m block starts [68]; however, a previous identical study found weak correlations ($r$ = 0.24 to 0.33) in an elite group of male sprinters [104]. Due to this variation, Maulder et al. (2006) [104] suggested that horizontal jump measures might be more effective for predicting sprint performance in athletes participating in sports requiring a variety of sprint running expressions but may not be valid for competitive level sprinters. They also considered that multiple jump measures, such as force and power, might better represent the dynamics of sprint running compared to jump distance alone. Nevertheless, given the relationship between jump distance and sprint performance, it can be hypothesised that the strength qualities required for achieving greater hop distances may also confer benefits to sprinting ability.

In addition to those investigating the relationship between TH tests and sprint performance, a 5-step jump test was reported to have very large negative correlations (*r* = −0.81) to 40 m sprint time [121] in a cohort of male sub-elite sports athletes. In the sprint training literature [161, 162] the QH test has been used extensively to determine readiness for competition and, therefore, is also worthy of further investigation to determine the relationship between TH and sprint performance, and additionally whether the QH test is a stronger predictor of sprint performance. Moreover, as Maulder et al. (2006) [104] suggested, it would be useful for a deterministic purpose, i.e., to quantify this relationship, to use kinetic measures (force or power) rather than just distance hopped.

Reactive strength, the ability to efficiently couple eccentric–concentric contractions [the stretch–shorten cycle (SSC)], is a metric that has garnered considerable attention. It is thought to be a fundamental determinant of many athletic qualities [82] and has shown to be highly correlated with vertical leg-spring stiffness [86]. This strength quality is typically represented as RSI, measured by the ratio between jump height and contact time in a drop jump [59] or by the ratio between jump height and time to take off ($RSI_{mod}$) in the CMJ [53], or the ratio of flight time to ground contact time [34], and it is sometimes referred to as the reactive strength ratio [73, 97]. Given the principle of specificity, it may make sense to calculate the RSI parallel to the principal line of movement when explicitly calculating $RSI_{hor}$ for sprinting performance. Davey et al. (2021) [44] examined whether such a measure (the ratio between flight and contact time) was reliable using a TH test. The between-session CVs were less than 5.5%, and the ICCs were greater than 0.70 across hops. Sarabon et al. (2023) [138] however, quantified the reliability of the TH flight time, hop distance, and contact time, and reported only moderate reliability (ICC = 0.67 - 0.74). Assuming that this reliability is acceptable, it is important to determine whether $RSI_{hor}$ as a metric has a high association with performance, thereby establishing its value as a tool for athletic monitoring and exercise prescription. A recent study [44] has investigated the utility of $RSI_{hor}$ from a TH test, finding variable correlations with 505 test performance (*r* = −0.76 to 0.23) and 10 m sprint performance (*r* = −0.50 to 0.43) in male volleyball players. $RSI_{hor}$ measures calculated from flight and ground contact times of unilateral multiple hopping tasks have also been shown to have a negligible to moderate relationship with sprint performances, ranging from 10 m to 100 m (*r* = 0.00 to −0.38) [139]. This was the first study to investigate $RSI_{hor}$ further than the TH test, and it noted that RSI continued to increase until the fifth hop, suggesting that a QH test should be enough multiple hops in series to understand an athlete's capability. However, further research is required to better understand the relationship between $RSI_{hor}$ and athletic performance, particularly in athletes accustomed to horizontal-focused movements over longer sprint distances.

Interestingly, both TH and QH assessments have been used for assessing elite sprinter's training readiness for competition, and to provide key insights into "an athlete's ability to express repeated peaks of strength in exercise with faster and faster movements" [161, 162]. According to Vittori [162], sprinters with good strength expression should hop seventy percent further for a QH than a TH. Whether this is the case has not been documented, and it may be that other measures, such as the $RSI_{hor}$, provide better insight as to that which differentiates sprint performance.

The TH is a movement that is implemented a great deal by practitioners interested in the neuromuscular function of athletes during rehabilitation and sports performance. The QH is less well researched, possibly due to the higher neuromuscular demands associated with the latter hops. The authors have noted increases of ~56% in maximal vertical force, ~236% in vertical braking impulse, and ~1147% in horizontal braking impulse across steps. Given the higher neuromuscular demands, the QH may be a better differentiator of sprint ability as compared to the TH test. Based on this and the preceding information, the aims of this study were threefold: (1) to examine the relationship between TH and QH distance with sprint performance and determine whether hop kinetic variables provide stronger relationships to sprinting ability than the kinematic/hop distances; (2) to explore the relationship between two methods of determining TH and QH $RSI_{hor}$ and sprint performance; and (3) to investigate whether the QH/TH ratio or $RSI_{hor}$ or other kinetic measures could differentiate between sprinters of different ability. It was hypothesised that (1) the correlations between TH and QH distances/sprint performances would be strong and that kinetic variables would provide stronger correlations to sprinting ability; (2) both methods (flight and distance) for determining $RSI_{hor}$ would be similarly correlated with sprint performance; and (3) the faster sprinters would have a greater percentage difference between their TH and QH ratios. The findings will provide practitioners with valuable insights into the potential utility of multiple hop tests for assessing, rehabilitation and enhancing athletic performance.

## 7.2 Methodology

### 7.2.1 Participants

Forty-four male sportsmen (age 20.1 ± 1.4 years; body mass 71.2 ± 8.6 kg; stature 171.9 ± 5.1 cm) from across various university sports (kendo, baseball, rowing, track athletics, field athletics, windsurfing, cycling, soccer, and basketball) volunteered to participate. All participants were required to be healthy and injury-free at the time of testing. Potential participants were excluded if they had any significant historical injuries (e.g., previous ruptures or tears to major tendons or ligaments [Achilles, ACL]), regardless of the post-injury training time. The study procedures followed the Declaration of Helsinki, and ethical approval was granted by the Auckland University of Technology Review Board (reference: 17/133) (Appendix I) and the National Institute of Fitness and Sports in Kanoya Review Board (reference: 8-123) (Appendix II). Informed consent was obtained before inclusion in the study (Appendices IV and V). Body mass was measured to the nearest 0.1 kg, and stature was measured according to the methodology set out by the International Society for the Advancement of Kinanthropometry [123] on a digital scale and stadiometer (Tanita DC-217A, Tokyo, Japan).

### 7.2.2 Procedures

Each participant attended a familiarisation session a minimum of three days prior to the first testing session, which included a standardised warm-up protocol that was repeated before the testing session. The warm-up included dynamic limb flexibility exercises (upper and lower), general movement to raise body temperature, explosive bounding movements to mimic test demands, and gradually intense sprinting over 30 m. The testing process started five minutes after the warm-up was completed.

The TH test protocol involved three hops on the same leg (Figure 13), while the QH test involved five hops on the same leg. Because of the very high stretch-load demands placed on the body by this test, three trials for TH and two trials for QH were completed in a randomised order for DOM and NDOM limbs, minimising the risk of injury, reducing acute overuse, and reducing fatigue effects. There was a two-minute rest period between the efforts before hopping on the other leg. Each hop began with the subject balancing on their hopping leg before propelling themselves forward for the number of contacts specified in the test. For all tests, the subjects landed on two feet after the final hop; contact with the ground with their hands after landing was permitted if the hopping foot did not move further forward during landing. This was performed to encourage each subject to achieve maximal horizontal displacement. Upper-limb motion was permitted during the hops, which replicated the motor patterns associated with athletic movements. Each subject was instructed to "reach the furthest horizontal distance in the shortest possible time".

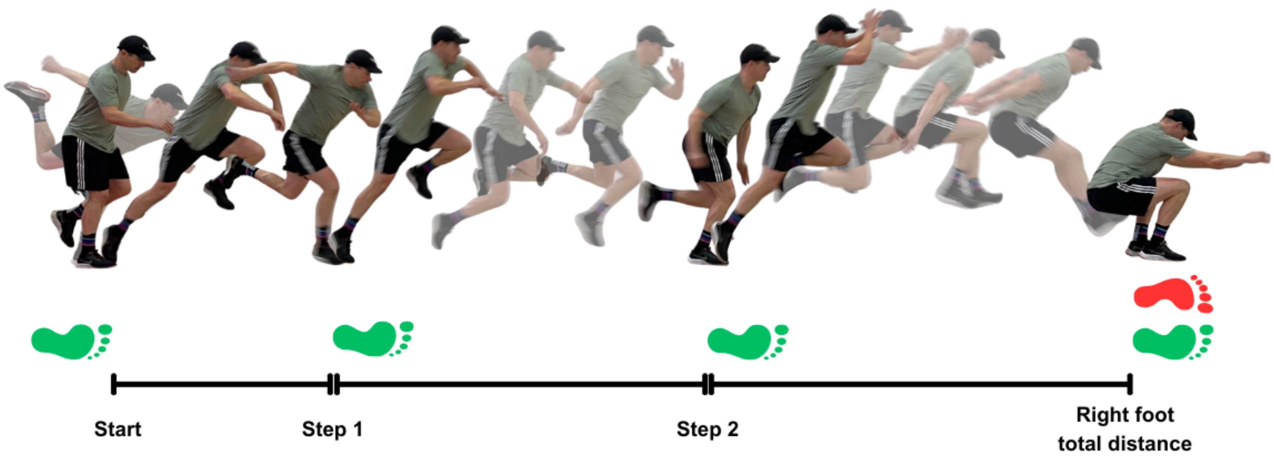


**Figure 13**. The sequence of a right foot TH test (green)

The sprint testing (Appendix VIII) and hop trials were conducted on an indoor synthetic track surface (Hasegawa Sports Facilities, Tokyo, Japan) that covered 54x inground force platforms in series (TF-90100, Tec Gihan, Kyoto, Japan), and were linked to a single computer that collected GRFs at a sampling rate of 1000 Hz. Force plate data were captured for each trial, exported, tagged, and stored for later analysis. The GRF signals collected during the hop trials were filtered using a 4th-order Butterworth low-pass digital filter with a 50 Hz cutoff frequency, and horizontal and vertical hop propulsive and braking kinetics were determined, with associated impulses calculated via the integration of force for each of the required periods. All variables were computed using a custom algorithm (MATLAB R2021a, Mathworks Inc., Natick, MA, USA).

### 7.2.3 Data Processing and Outcome Measures

Touch-down and take-off detection were identified in the filtered data by a 20 N vertical GRF threshold. Horizontal CoM velocity ($V_H$ as a function of time) was calculated from the initial movement to the end of the trial using the methods outlined by Colyer, Nagahara, and Salo [37]. Per this method, the impulse–momentum relationship was used to determine instantaneous $V_H$ throughout the entire sprint from the $IMP_{AP}$ and using estimated aerodynamic drag [136]. Sprint times (5 m to 45 m) were derived from the integral of the $V_H$ data. Hop ratios were determined by dividing the mean QH distance by the mean TH distance. RSI was determined using the methods outlined by Sarabon et al. [138] for each step and also as an average (Total $RSI_{hor}$) for each hop trial using two methods; firstly, $RSI_{hor-DIST}$ was calculated by dividing the hop distance by the previous ground contact time, and secondly, $RSI_{hor-FT}$ was calculated by dividing the hop flight time by the previous ground contact time. Total $RSI_{hor}$ was determined by dividing total hop distance or total flight time by the sum of all ground contacts.

### 7.2.4 Statistical Analysis

Statistical analyses were performed with Jeffrey's Amazing Statistics Program (JASP) software (version 0.18.3; Amsterdam, The Netherlands). Using descriptive statistics (means and standard deviations), centrality and spread were calculated and presented in the tables. Assumptions of univariate normality, outliers, and sphericity were assessed. Outlier analysis was conducted using boxplots, and values larger than three standard deviations were manually omitted from any further analysis. The Shapiro–Wilk test [145] was used to evaluate normality, and Q-Q plots were used to visually assess kurtosis and skewness. Of interest was whether the kinematic and kinetic variables could distinguish between sprinters of different ability. A paired sample *t*-test was conducted to assess whether there were significant differences between the DOM and NDOM limbs, no statistically significant differences between the two limbs were detected, prompting the pooling of the data for subsequent analysis. The sportsmen were divided into two groups (fast and slow), consisting of the top fifteen and bottom fifteen performers for 10 m and 40 m sprint times, which were used as proxies for accelerative and top speed capability. Independent *t*-tests were conducted to identify any significant differences ($p < 0.05$) in kinetics, hop ratios, and $RSI_{hor}$ between these groups. A Levene's test was used to test the assumption that variances are equal across both groups. To explore the relationship between hop distance, $RSI_{hor}$, and sprint performance, a series of

Pearson's correlations were conducted, with the significance set at $p < 0.05$ and interpreted as weak (0.1–0.3), moderate (0.4–0.6), or strong (0.7–0.9) [2].

## 7.3 Results

The inter-relationship between speed measures and total hop distances is presented in Table 15. A near-perfect correlation was observed between the TH and QH distances. As the distance increased from 10 m to 40 m, the strength of the correlations between the sprint times and both the TH and QH distances also increased, with very high negative and statistically significant ($p < 0.05$) correlations ranging from $r = -0.700$ to $-0.796$. The differences in the TH and QH correlations were negligible, ranging from 0.006 to 0.011.

**Table 15.** Inter-relationships between speed measures and TH and QH distance

| | | **10 m** | **20 m** | **40 m** |
|---|---|---|---|---|
| TH distance | Pearson's *r* | −0.705 | −0.760 | −0.795 |
| | *p*-value | <0.001 | <0.001 | <0.001 |
| QH distance | Pearson's *r* | −0.700 | −0.759 | −0.796 |
| | *p*-value | <0.001 | <0.001 | <0.001 |

The means and standard deviations for the kinetic variables for TH and QH are provided in Table 16. In terms of the relationship between TH and QH kinetic measures and sprint times (10 m and 40 m) the following was observed: the relationships between the kinetic measures and 10 m and 40 m sprint times were weak to moderate ($r < -0.554$). Among the kinetic measures, relative maximal vertical force exhibited the strongest correlation, particularly across the TH and QH sequences ($r = -0.554$ to $-0.350$). Relative net vertical impulse was found to have a weak relationship across steps with sprint times ($r = -0.360$ to $-0.270$), as too was the relative vertical braking impulse across ($r = -0.339$ to $0.066$). Moderate to negligible correlations were found between relative vertical propulsive impulse with sprint times ($r = -0.404$ to $0.059$), with the strongest relationships observed in the initial steps, particularly for shorter sprint distances. Moderate to weak correlations were observed between net relative horizontal impulse and sprint times ($r = -0.449$ to 0.147), with stronger relationships observed in the first step across all sprint distances. A weak relationship was seen between relative horizontal braking impulse and sprint times ($r = -0.224$ to 0.259). Moderate to negligible correlations were seen between relative horizontal propulsive impulse and sprint times ($r = -0.477$ to 0.033), with stronger associations in the initial steps and weaker correlations in the final step.

The means and standard deviations for all RSI variables are presented in Table 17. $RSI_{hor\text{-}DIST}$ ($r = -0.453$ to $-0.707$) was found to have stronger relationships with sprint performance than $RSI_{hor\text{-}FT}$ ($r = -0.270$ to $-0.668$) across all steps and particularly over the initial 5–10 m shorter distances and between fast and slow groups (Table 17). The strength of association of Total $RSI_{hor}$ increased with sprinting distance (0.490 to 0.707; $p < 0.001$) for both TH and QH (Figure 14).

**Table 16.** Descriptive statistics and Pearson (*r*) correlations and *p*-values between kinetic variables (TH, QH) and sprint times (10 m and 40 m)

| | **TH** | | | | | **QH** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **10 m** | | **40 m** | | | **10 m** | | **40 m** | |
| **Kinetic Variable** | **Mean ± SD** | ***r*** | ***p*** | ***r*** | ***p*** | **Mean ± SD** | ***r*** | ***p*** | ***r*** | ***p*** |
| Maximal Vertical Force 1 | 32.5 ± 4.63 | −0.366 | 0.016 | −0.451 | 0.002 | 32.1 ± 4.22 | −0.279 | 0.070 | −0.350 | 0.021 |
| Maximal Vertical Force 2 | 42.0 ± 7.60 | −0.416 | 0.005 | −0.501 | <0.001 | 39.7 ± 7.15 | −0.484 | 0.001 | −0.553 | <0.001 |
| Maximal Vertical Force 3 | | | | | | 45.1 ± 8.76 | −0.336 | 0.026 | −0.467 | 0.001 |
| Maximal Vertical Force 4 | | | | | | 50.7 ± 10.5 | −0.452 | 0.002 | −0.554 | <0.001 |
| Net Vertical Impulse 1 | 5.67 ± 0.439 | −0.296 | 0.051 | −0.310 | 0.040 | 5.48 ± 0.442 | −0.286 | 0.060 | −0.307 | 0.043 |
| Net Vertical Impulse 2 | 5.87 ± 0.338 | −0.337 | 0.029 | −0.335 | 0.030 | 5.48 ± 0.415 | −0.319 | 0.037 | −0.358 | 0.018 |
| Net Vertical Impulse 3 | | | | | | 5.60 ± 0.397 | −0.270 | 0.080 | −0.338 | 0.027 |
| Net Vertical Impulse 4 | | | | | | 5.88 ± 0.343 | −0.311 | 0.048 | −0.360 | 0.021 |
| Vertical Braking Impulse 1 | 1.33 ± 0.626 | −0.043 | 0.785 | −0.054 | 0.736 | 1.04 ± 0.579 | 0.066 | 0.672 | 0.026 | 0.019 |
| Vertical Braking Impulse 2 | 2.58 ± 0.461 | −0.110 | 0.477 | −0.155 | 0.314 | 2.02 ± 0.372 | −0.148 | 0.337 | −0.190 | 0.218 |
| Vertical Braking Impulse 3 | | | | | | 2.80 ± 0.373 | −0.023 | 0.884 | −0.136 | 0.389 |
| Vertical Braking Impulse 4 | | | | | | 3.55 ± 0.580 | −0.267 | 0.080 | −0.339 | 0.024 |
| Vertical Propulsive Impulse 1 | 4.36 ± 0.431 | −0.250 | 0.101 | −0.237 | 0.122 | 4.46 ± 0.396 | −0.404 | 0.007 | −0.368 | 0.015 |
| Vertical Propulsive Impulse 2 | 3.32 ± 0.481 | −0.209 | 0.173 | −0.179 | 0.246 | 3.51 ± 0.293 | −0.242 | 0.128 | −0.283 | 0.073 |
| Vertical Propulsive Impulse 3 | | | | | | 2.85 ± 0.243 | −0.330 | 0.029 | −0.262 | 0.085 |
| Vertical Propulsive Impulse 4 | | | | | | 2.42 ± 0.509 | 0.037 | 0.810 | 0.059 | 0.703 |
| Net Horizontal Impulse 1 | 0.700 ± 0.157 | −0.306 | 0.046 | −0.354 | 0.020 | 0.780 ± 0.154 | −0.436 | 0.003 | −0.449 | 0.002 |
| Net Horizontal Impulse 2 | 0.305 ± 0.148 | −0.148 | 0.337 | −0.162 | 0.292 | 0.461 ± 0.091 | −0.171 | 0.280 | −0.200 | 0.205 |
| Net Horizontal Impulse 3 | | | | | | 0.196 ± 0.094 | −0.234 | 0.135 | −0.185 | 0.242 |
| Net Horizontal Impulse 4 | | | | | | −0.050 ± 0.186 | 0.141 | 0.366 | 0.147 | 0.346 |
| Horizontal Braking Impulse 1 | −0.048 ± 0.023 | −0.164 | 0.306 | −0.224 | 0.160 | −0.033 ± 0.017 | −0.179 | 0.263 | −0.178 | 0.266 |
| Horizontal Braking Impulse 2 | −0.191 ± 0.048 | −0.095 | 0.541 | −0.142 | 0.356 | −0.113 ± 0.035 | −0.026 | 0.869 | 0.017 | 0.912 |
| Horizontal Braking Impulse 3 | | | | | | −0.257 ± 0.044 | 0.118 | 0.470 | 0.165 | 0.308 |
| Horizontal Braking Impulse 4 | | | | | | −0.400 ± 0.094 | 0.211 | 0.180 | 0.259 | 0.098 |
| Horizontal Propulsive Impulse 1 | 0.756 ± 0.135 | −0.332 | 0.028 | −0.354 | 0.018 | 0.820 ± 0.138 | −0.477 | 0.001 | −0.477 | 0.001 |
| Horizontal Propulsive Impulse 2 | 0.500 ± 0.109 | −0.177 | 0.250 | −0.191 | 0.214 | 0.583 ± 0.074 | −0.281 | 0.068 | −0.337 | 0.027 |
| Horizontal Propulsive Impulse 3 | | | | | | 0.445 ± 0.069 | −0.368 | 0.014 | −0.324 | 0.032 |
| Horizontal Propulsive Impulse 4 | | | | | | 0.350 ± 0.105 | 0.033 | 0.834 | 0.032 | 0.836 |

**Key:** SD = standard deviation; force variables = N.kg; impulse variables = Ns.kg

**Table 17.** Descriptive statistics of TH and QH RSI and Pearson (*r*) correlations and *p*-values with sprint performance

| | **Mean ± SD** | **Range** | **5 m** | | **10 m** | | **20 m** | | **40 m** | |
|---|---|---|---|---|---|---|---|---|---|---|
| **TH** | | | ***r*** | ***p*** | ***r*** | ***p*** | ***r*** | ***p*** | ***r*** | ***p*** |
| Step 1–2 RSI$_{\text{hor-DIST}}$ | 7.26 ± 1.39 | 4.94 to 10.51 | −0.468 | 0.001 | −0.535 | <0.001 | −0.595 | <0.001 | −0.641 | <0.001 |
| Step 1–2 RSI$_{\text{hor-FT}}$ | 1.18 ± 0.25 | 0.68 to 1.82 | −0.350 | 0.020 | −0.438 | 0.003 | −0.496 | <0.001 | −0.549 | <0.001 |
| Step 2–3 RSI$_{\text{hor-DIST}}$ | 10.71 ± 2.18 | 7.12 to 15.72 | −0.477 | 0.001 | −0.555 | <0.001 | −0.626 | <0.001 | −0.680 | <0.001 |
| Step 2–3 RSI$_{\text{hor-FT}}$ | 1.71 ± 0.34 | 1.09 to 2.46 | −0.434 | 0.003 | −0.518 | <0.001 | −0.590 | <0.001 | −0.647 | <0.001 |
| Total RSI$_{\text{hor-DIST}}$ | 11.99 ± 2.21 | 8.48 to 16.78 | −0.490 | <0.001 | −0.567 | <0.001 | −0.634 | <0.001 | −0.685 | <0.001 |
| Total RSI$_{\text{hor-FT}}$ | 1.44 ± 0.28 | 0.88 to 2.12 | −0.391 | 0.009 | −0.482 | <0.001 | −0.544 | <0.001 | −0.562 | <0.001 |
| **QH** | | | | | | | | | | |
| Step 1–2 RSI$_{\text{hor-DIST}}$ | 7.30 ± 1.23 | 4.74 to 10.19 | −0.467 | 0.001 | −0.547 | <0.001 | −0.609 | <0.001 | −0.653 | <0.001 |
| Step 1–2 RSI$_{\text{hor-FT}}$ | 1.17 ± 0.23 | 0.72 to 1.82 | −0.270 | 0.076 | −0.357 | 0.017 | −0.408 | 0.006 | −0.455 | 0.002 |
| Step 2–3 RSI$_{\text{hor-DIST}}$ | 9.12 ± 1.69 | 5.90 to 12.93 | −0.453 | 0.002 | −0.548 | <0.001 | −0.619 | <0.001 | −0.671 | <0.001 |
| Step 2–3 RSI$_{\text{hor-FT}}$ | 1.36 ± 0.27 | 0.80 to 2.07 | −0.319 | 0.035 | −0.413 | 0.005 | −0.480 | <0.001 | −0.539 | <0.001 |
| Step 3–4 RSI$_{\text{hor-DIST}}$ | 9.93 ± 2.03 | 6.28 to 14.0 | −0.461 | 0.002 | −0.532 | <0.001 | −0.597 | <0.001 | −0.643 | <0.001 |
| Step 3–4 RSI$_{\text{hor-FT}}$ | 1.46 ± 0.31 | 0.83 to 2.30 | −0.315 | 0.037 | −0.403 | 0.007 | −0.475 | 0.001 | −0.542 | <0.001 |
| Step 4–5 RSI$_{\text{hor-DIST}}$ | 12.18 ± 2.82 | 7.74 to 18.4 | −0.507 | <0.001 | −0.583 | <0.001 | −0.639 | <0.001 | −0.674 | <0.001 |
| Step 4–5 RSI$_{\text{hor-FT}}$ | 1.89 ± 0.43 | 1.04 to 2.78 | −0.467 | 0.001 | −0.553 | <0.001 | −0.615 | <0.001 | −0.661 | <0.001 |
| Total RSI$_{\text{hor-DIST}}$ | 11.17 ± 2.02 | 7.33 to 15.6 | −0.506 | <0.001 | −0.591 | <0.001 | −0.655 | <0.001 | −0.700 | <0.001 |
| Total RSI$_{\text{hor-FT}}$ | 1.45 ± 0.28 | 0.84 to 2.15 | −0.391 | <0.001 | −0.482 | <0.001 | −0.544 | <0.001 | −0.597 | <0.001 |

**Key:** SD = standard deviation; RSI = reactive strength index (m·s$^{-1}$); $_{\text{hor-DIST}}$ = horizontal distance/ground contact time; $_{\text{hor-FT}}$ = horizontal flight time/ground contact time

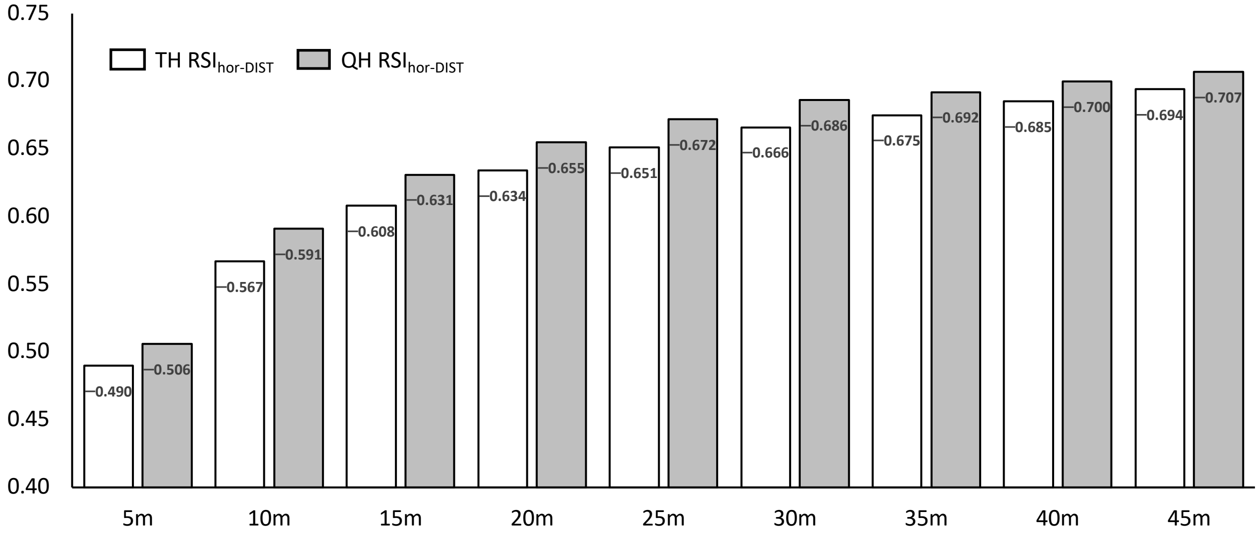


**Figure 14.** Changes in the correlation coefficients (Pearson's *r*) between 5 m to 45 m sprint times and TH RSI$_{\text{hor-DIST}}$ and QH RSI$_{\text{hor-DIST}}$

The means and standard deviations for the 10 m and 40 m fast and slow groups and their differences are shown in Tables 18 and 19. In terms of the 10 m times, faster sprinters were found to produce significantly greater maximal vertical force across all hops (8.55 to 25.6% Δ) for both the TH and QH testing (ES = 0.784 - 1.306), significantly greater vertical propulsive impulse (8.41% Δ) on the first hop of QH testing, significantly greater net horizontal impulse on the first hop (20.3% Δ) of the QH, and significantly greater horizontal propulsive impulse across the first three hops (10.1 to 17.8% Δ) in the QH (ES = 0.818 - 1.159). With regards to the 40 m times, faster sprinters were found to produce significantly greater maximal vertical force across all hops (9.84 to 30.3% Δ) for both the TH and QH testing (ES = 0.909 - 1.644), significantly greater net horizontal impulse on the first hop (19.7% Δ) in the QH, and significantly greater horizontal propulsive impulse in the first hop (12.9 to 17.4% Δ) in the TH and QH.

**Table 18.** Descriptive statistics for TH variables and *t*-test for independent samples with *p*-values and ES for slow and fast sprint groups (10 m and 40 m)

| | **10 m** | | | | **40 m** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Slow** | **Fast** | | | **Slow** | **Fast** | | |
| **Kinetic Variable** | **Mean ± SD** | **Mean ± SD** | ***p*** | ***d*** | **Mean ± SD** | **Mean ± SD** | ***p*** | ***d*** |
| Maximal Vertical Force 1 | 30.2 ± 3.80 | 33.5 ± 3.47 | 0.024 | 0.892 | 30.1 ± 3.83 | 34.3 ± 3.61 | 0.006 | 1.120 |
| Maximal Vertical Force 2 | 37.9 ± 6.05 | 44.8 ± 7.04 | 0.008 | 1.046 | 38.2 ± 5.98 | 46.2 ± 6.86 | 0.002 | 1.240 |
| Net Vertical Impulse 1 | 5.57 ± 0.447 | 5.76 ± 0.447 | 0.245 | 0.433 | 5.51 ± 0.424 | 5.72 ± 0.442 | 0.188 | 0.493 |
| Net Vertical Impulse 2 | 5.78 ± 0.416 | 5.98 ± 0.337 | 0.166 | 0.529 | 5.74 ± 0.379 | 5.96 ± 0.334 | 0.102 | 0.629 |
| Vertical Braking Impulse 1 | 1.22 ± 0.642 | 1.31 ± 0.480 | 0.651 | 0.170 | 1.21 ± 0.665 | 1.26 ± 0.475 | 0.803 | 0.096 |
| Vertical Braking Impulse 2 | 2.44 ± 0.441 | 2.52 ± 0.446 | 0.663 | 0.161 | 2.49 ± 0.510 | 2.53 ± 0.461 | 0.803 | 0.092 |
| Vertical Propulsive Impulse 1 | 4.32 ± 0.480 | 4.44 ± 0.405 | 0.460 | 0.274 | 4.35 ± 0.523 | 4.45 ± 0.405 | 0.550 | 0.221 |
| Vertical Propulsive Impulse 2 | 3.29 ± 0.303 | 3.51 ± 0.524 | 0.185 | 0.496 | 3.21 ± 0.402 | 3.44 ± 0.585 | 0.222 | 0.456 |
| Net Horizontal Impulse 1 | 0.655 ± 0.144 | 0.751 ± 0.143 | 0.080 | 0.664 | 0.669 ± 0.159 | 0.777 ± 0.134 | 0.055 | 0.731 |
| Net Horizontal Impulse 2 | 0.299 ± 0.102 | 0.367 ± 0.166 | 0.182 | 0.500 | 0.289 ± 0.121 | 0.356 ± 0.173 | 0.223 | 0.455 |
| Horizontal Braking Impulse 1 | 0.054 ± 0.027 | −0.047 ± 0.017 | 0.420 | 0.304 | −0.052 ± 0.029 | −0.043 ± 0.019 | 0.343 | 0.359 |
| Horizontal Braking Impulse 2 | −0.193 ± 0.038 | −0.180 ± 0.052 | 0.416 | 0.301 | −0.193 ± 0.037 | −0.177 ± 0.053 | 0.362 | 0.339 |
| Horizontal Propulsive Impulse 1 | 0.725 ± 0.119 | 0.808 ± 0.123 | 0.070 | 0.689 | 0.735 ± 0.129 | 0.830 ± 0.107 | 0.037 | 0.800 |
| Horizontal Propulsive Impulse 2 | 0.492 ± 0.078 | 0.551 ± 0.123 | 0.130 | 0.570 | 0.482 ± 0.093 | 0.545 ± 0.120 | 0.119 | 0.587 |

**Key:** SD = standard deviation; force variables = N.kg; impulse variables = Ns.kg; *d* = Cohen's d for effect size

**Table 19.** Descriptive statistics for QH kinetic variables and *t*-test for independent samples with *p*-values and ES for slow and fast sprint groups (10 m and 40 m)

| | **10 m** | | | | **40 m** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Slow** | **Fast** | | | **Slow** | **Fast** | | |
| **Kinetic Variable** | **Mean ± SD** | **Mean ± SD** | ***p*** | ***d*** | **Mean ± SD** | **Mean ± SD** | ***p*** | ***d*** |
| Maximal Vertical Force 1 | 30.4 ± 2.94 | 33.0 ± 3.59 | 0.044 | 0.784 | 30.5 ± 2.87 | 33.5 ± 3.74 | 0.021 | 0.909 |
| Maximal Vertical Force 2 | 35.9 ± 6.13 | 43.4 ± 6.24 | 0.002 | 1.214 | 35.9 ± 6.10 | 45.1 ± 6.00 | <0.001 | 1.514 |
| Maximal Vertical Force 3 | 40.7 ± 7.02 | 47.0 ± 7.52 | 0.025 | 0.864 | 40.9 ± 6.89 | 50.0 ± 7.88 | 0.002 | 1.236 |
| Maximal Vertical Force 4 | 44.0 ± 6.95 | 55.4 ± 10.2 | 0.001 | 1.306 | 44.5 ± 6.76 | 58.0 ± 9.45 | <0.001 | 1.644 |
| Net Vertical Impulse 1 | 5.39 ± 0.444 | 5.56 ± 0.477 | 0.303 | 0.383 | 5.31 ± 0.406 | 5.55 ± 0.457 | 0.131 | 0.568 |
| Net Vertical Impulse 2 | 5.42 ± 0.494 | 5.59 ± 0.368 | 0.298 | 0.387 | 5.35 ± 0.468 | 5.62 ± 0.374 | 0.091 | 0.640 |
| Net Vertical Impulse 3 | 5.55 ± 0.448 | 5.71 ± 0.373 | 0.299 | 0.383 | 5.49 ± 0.450 | 5.73 ± 0.380 | 0.121 | 0.585 |
| Net Vertical Impulse 4 | 5.79 ± 0.390 | 5.97 ± 0.352 | 0.192 | 0.497 | 5.75 ± 0.368 | 5.94 ± 0.333 | 0.158 | 0.550 |
| Vertical Braking Impulse 1 | 1.14 ± 0.604 | 0.945 ± 0.542 | 0.367 | −0.303 | 1.04 ± 0.663 | 0.985 ± 0.504 | 0.794 | −0.098 |
| Vertical Braking Impulse 2 | 2.02 ± 0.474 | 2.00 ± 0.273 | 0.914 | −0.040 | 1.97 ± 0.484 | 2.07 ± 0.308 | 0.539 | 0.227 |
| Vertical Braking Impulse 3 | 2.81 ± 0.339 | 2.77 ± 0.392 | 0.786 | −0.102 | 2.76 ± 0.370 | 2.82 ± 0.372 | 0.649 | 0.171 |
| Vertical Braking Impulse 4 | 3.27 ± 0.604 | 3.47 ± 0.405 | 0.278 | 0.404 | 3.32 ± 0.655 | 3.56 ± 0.553 | 0.303 | 0.383 |
| Vertical Propulsive Impulse 1 | 4.28 ± 0.424 | 4.64 ± 0.360 | 0.021 | 0.909 | 4.30 ± 0.439 | 4.49 ± 0.342 | 0.055 | 0.747 |
| Vertical Propulsive Impulse 2 | 3.43 ± 0.271 | 3.60 ± 0.325 | 0.134 | 0.564 | 3.40 ± 0.238 | 3.57 ± 0.321 | 0.120 | 0.585 |
| Vertical Propulsive Impulse 3 | 2.80 ± 0.279 | 2.97 ± 0.242 | 0.088 | 0.645 | 2.78 ± 0.265 | 2.92 ± 0.229 | 0.117 | 0.590 |
| Vertical Propulsive Impulse 4 | 2.57 ± 0.517 | 2.56 ± 0.390 | 0.991 | −0.004 | 2.47 ± 0.580 | 2.50 ± 0.474 | 0.916 | 0.039 |
| Net Horizontal Impulse 1 | 0.701 ± 0.132 | 0.843 ± 0.127 | 0.006 | 1.096 | 0.721 ± 0.155 | 0.863 ± 0.121 | 0.009 | 1.020 |
| Net Horizontal Impulse 2 | 0.431 ± 0.082 | 0.483 ± 0.095 | 0.129 | 0.594 | 0.446 ± 0.010 | 0.473 ± 0.098 | 0.476 | 0.274 |
| Net Horizontal Impulse 3 | 0.168 ± 0.085 | 0.219 ± 0.098 | 0.143 | 0.561 | 0.186 ± 0.101 | 0.217 ± 0.076 | 0.357 | 0.348 |
| Net Horizontal Impulse 4 | 0.039 ± 0.130 | −0.005 ± 0.162 | 0.422 | −0.303 | 0.010 ± 0.182 | −0.019 ± 0.175 | 0.661 | −0.165 |
| Horizontal Braking Impulse 1 | −0.036 ± 0.013 | −0.031 ± 0.015 | 0.296 | 0.404 | −0.034 ± 0.014 | −0.029 ± 0.015 | 0.385 | 0.334 |
| Horizontal Braking Impulse 2 | −0.123 ± 0.033 | −0.109 ± 0.035 | 0.295 | 0.390 | −0.116 ± 0.037 | −0.113 ± 0.037 | 0.846 | 0.072 |
| Horizontal Braking Impulse 3 | −0.256 ± 0.052 | −0.269 ± 0.029 | 0.424 | −0.307 | −0.253 ± 0.052 | −0.261 ± 0.031 | 0.643 | −0.180 |
| Horizontal Braking Impulse 4 | −0.351 ± 0.082 | −0.386 ± 0.076 | 0.249 | −0.438 | −0.349 ± 0.085 | −0.393 ± 0.085 | 0.174 | −0.529 |
| Horizontal Propulsive Impulse 1 | 0.746 ± 0.114 | 0.879 ± 0.116 | 0.004 | 1.159 | 0.764 ± 0.1355 | 0.897 ± 0.105 | 0.006 | 1.094 |
| Horizontal Propulsive Impulse 2 | 0.555 ± 0.065 | 0.611 ± 0.074 | 0.036 | 0.818 | 0.563 ± 0.075 | 0.606 ± 0.074 | 0.130 | 0.580 |
| Horizontal Propulsive Impulse 3 | 0.422 ± 0.057 | 0.480 ± 0.076 | 0.025 | 0.864 | 0.428 ± 0.061 | 0.470 ± 0.072 | 0.097 | 0.627 |
| Horizontal Propulsive Impulse 4 | 0.370 ± 0.103 | 0.377 ± 0.103 | 0.847 | 0.071 | 0.359 ± 0.112 | 0.368 ± 0.110 | 0.832 | 0.078 |

**Key:** SD = standard deviation; force variables = N.kg; impulse variables = Ns.kg; *d* = Cohen's *d* for ES

Hop ratios did not distinguish ($p < 0.05$) between fast and slow groups for sprinting (Table 20). The fast group QH distance was approximately 72.5% greater than the TH distance for both the 10 m and 40 m, whereas the slower group differences were 71% across both sprint distances. However, the TH and QH RSI$_{\text{hor}}$ measures were found to be significantly different between the fast and slow sprinters. The differences between the TH and QH $RSI_{hor}$ values of the fastest and slowest groups was ~14.5 to 22.5% ($p < 0.001$) for both the 10 m and 40 m distances.

**Table 20.** The sprint times and hop ratios for groups, separated by 10 m and 40 m times

| | Sprint Time (s) | Hop Ratio | ***p*** | TH $RSI_{hor-DIST}$ | ***p*** | QH $RSI_{hor-DIST}$ | ***p*** |
|---|---|---|---|---|---|---|---|
| **10 m Sprint** | | | | | | | |
| Group 1 (fast) | 1.60 | 1.73 ± 0.034 | - | 13.1 ± 2.10 | - | 11.8 ± 1.08 | - |
| Group 2 (slow) | 1.78 | 1.71 ± 0.044 | 0.222 | 10.5 ± 1.52 | <0.001 | 10.1 ± 1.01 | <0.001 |
| **40 m Sprint** | | | | | | | |
| Group 1 (fast) | 5.10 | 1.72 ± 0.036 | - | 13.8 ± 2.20 | - | 12.8 ± 1.92 | - |
| Group 2 (slow) | 5.71 | 1.71 ± 0.046 | 0.434 | 10.7 ± 1.55 | <0.001 | 9.9 ± 1.59 | <0.001 |

## 7.4 Discussion

The TH and to a lesser extent the QH are movements that provide physiotherapists, as well as strength and conditioning coaches and technical coaches, with valuable insights into neuromuscular function. Improving understanding around the utility of these jumps and their associated measures provided an overarching focus for this research. Specifically, the aims of this study were threefold: (1) to examine the relationship between TH and QH distance and sprint performance, and to determine whether hop kinetic variables provide stronger relationships to sprinting ability than kinematic/hop distances; (2) to explore the relationship between two methods of determining TH and QH $RSI_{hor}$ and sprint performance; (3) to investigate whether the QH/TH ratio or $RSI_{hor}$ and other kinetic measures could differentiate between sprinters of different ability. The main findings were as follows: (1) TH and QH distances were strongly correlated with 10 m, 20 m, and 40 m sprint times ($r = 0.70$ to 0.80), while the relationship between the kinetic measures and sprint times was weak to moderate ($r < -0.55$); (2) the strength of the association between $RSI_{hor}$ and sprint performance increased with sprint distance ($r = 0.49$ to 0.71; $p < 0.001$), and $RSI_{hor}$ calculated from jump distance was a stronger predictor of sprint performance than calculation from flight time; (3) hop ratios did not differentiate between fast and slow sprinters, whereas $\mathrm{RSI}_{\mathrm{hor}}$ was able to; (4) there were significant differences in some kinetic measures of TH and QH tests that differentiated fast and slow sprinters; and (5) given the small differences between the TH and QH results, there would seem little value in including both hops in the assessment of sprint-related performance.

The TH and QH distances were strongly correlated with 10 m, 20 m, and 40 m sprint times ($r = 0.70$ to 0.80), with the strength of association increasing with sprint distance. The results of this study were consistent with the previously reported relationships between multiple hop distances and sprint performance, both for recreational ($r = 0.68$ to 0.86) athletes [33, 103] and sub-elite ($r = 0.84$ to 0.89) sprinters [68], and likely due the apparent diverse skill and sprint competency level of the cohort in this study.

Maulder et al. (2006) [104] proposed that predictions of sprint performance using horizontal jump measures might be more effective for athletes involved in sports requiring a wide range of sprinting expressions, but less applicable for competitive-level sprinters. They also suggested that more sensitive measures, such as force and power, might provide a better reflection of what occurs during sprint running compared to jumping distance alone. Our findings in this cohort of sportsmen suggests that while kinetic variables can explain some of the variance associated with sprinting, they were not strong predictors of sprint performance in this cohort. The general relationships between the hop GRFs and sprint performance were weak to moderate ($r < -0.55$). The maximal vertical forces seen in both TH and QH tests were shown to have the strongest relationship with sprint performance, and the strength of this relationship increased with sprinting distance over 5 m to 45 m. This finding is consistent with previously reported characteristics of elite sprint performance, whereby maximal velocity mechanics are constrained by the athlete's capacity to generate sufficient vertical impulse during ground contact [167]. This vertical impulse is critical for achieving adequate aerial time, thereby facilitating effective repositioning of the swing limb in preparation for the subsequent step [166].

Of interest was the relationship between the two methods of calculating TH and QH $RSI_{hor}$ and their relationship to sprint performance. The strength of the association between $RSI_{hor}$ and sprint performance increased with sprint distance ($r = 0.49$ to $0.71$; $p < 0.001$), with $RSI_{hor}$ calculated from jump distance showing a stronger correlation with sprint performance than when calculated from flight time (see Figure 14). Sarabon et al. (2023) [138] investigated the utility of $RSI_{hor\text{-}DIST}$ during TH assessments, finding small to moderate negative correlations with 505 change-of-direction test performance ($r = -0.15$ to $-0.45$) and 10 m sprint performance ($r = -0.03$ to $-0.16$) in male volleyball players. They reported $RSI_{hor\text{-}DIST}$ values ranging from 5.24 to 7.57 $m \cdot s^{-1}$, whereas in this study, TH assessments yielded values between 7.26 and 10.71 $m \cdot s^{-1}$, with stronger correlations with sprint performance ($r = -0.49$ to $-0.69$). This stronger relationship may be attributed to the higher reactive strength capacity of the subjects in this study. The mean hop distance in our sample was 6.43 m (± 0.67), compared to 5.91 m (± 0.51) in the Sarabon et al. [138] study, with our participants also demonstrating shorter ground contact times, which also amplifies the resulting RSI.

Another focus of the research was to determine whether the QH/TH ratio or $RSI_{hor}$ could differentiate between sprinters of differing ability. According to Vittori, sprinters with a capacity to express strength whilst sprinting should be able to hop approximately 70% further in a QH compared to a TH. However, our findings indicated that the hop ratio could not ($p < 0.05$) differentiate between fast and slow sprinters, as both group QH to TH differences were 71 to 72.5% ($p > 0.05$). While it might seem intuitive that athletes capable of achieving higher stretch-loads in a QH would also demonstrate faster sprinting speeds, our study, conducted with a heterogeneous sample, did not provide any evidence to support this hypothesis. Rather, it seems that $RSI_{hor}$ is a better variable to differentiate sprinting ability, and, therefore, most likely a better variable to measure and monitor. It also appears that $RSI_{hor}$ values from the TH assessments were just as strongly correlated with sprint distance as those from the QH test, suggesting that the additional injury risk associated with the QH may not be justified in a training-assessment context. Nevertheless, in a training environment, the QH might still be valuable for eliciting the higher stretch–load stimuli for those athletes ready for such incremental loading.

## 7.5 Conclusions and Practical Applications

Multiple hops offer an easy, valid, and reliable method for assessing neuromuscular function and are commonly used by physiotherapists, strength and conditioning coaches, and technical coaches. The utility and interpretation of these tests is usually based on the distance jumped. The focus of this article was to determine if other kinematic and kinetic measures could enhance the diagnostic value of TH and QH assessments, within a sports performance/sprint context. With this in mind, the findings were as follows.

Both TH and QH distances were strongly correlated with 10 m, 20 m, and 40 m sprint times, which have applications for assessment and training. For example, changes in the distance jumped should correspond to quicker sprint times (especially for longer distance sprints), which could be monitored between official timing light or radar assessments. In terms of training, using multiple hops as a training option to improve sprint times is certainly supported by the results of this study.

$RSI_{hor}$ calculated from jump distance was a stronger predictor of sprint performance than calculation from flight time, and it is recommended as the variable of choice for measuring horizontal reactivity. This can be performed with force plates, or by using more readily available smartphone AI-based digitizing applications, such as Vuemotion (Sydney, Australia); however, using flight time in the calculation can offer a more practical approach for field assessments for those without expensive analysis tools, as simple smartphone video technology has been shown to be both valid and reliable for this purpose [149, 150].

Most of the movement strategy kinetic variables did not correlate strongly to the outcome variables (jump distance/sprint times) in this cohort. Of the kinetic measures investigated, maximal vertical force and horizontal propulsive impulse were found to be correlated best with the 10 m and 40 m times, and, as such, are potentially the best variables to measure, monitor, and train athletes if force plate technology is available.

It would seem that the hop ratio between the TH and QH cannot differentiate sprint ability in sportsmen; however, $RSI_{hor}$ can, and, therefore, this measure could be used to measure and monitor athletes, or for talent identification purposes.

Given the high collinearity between the TH and QH tests, it would seem prudent to measure and monitor only one of the hops. The stretch-loads associated with the QH exceed that of the TH, and, therefore, decisions on the hop used in an assessment battery may be made around the unilateral strength–power qualities and athleticism of the athletes who are involved.

One limitation of this study was the homogeneity of the sample. While it encompassed a diverse range of participants from various sports requiring both skill and a variety of strength qualities, the sample was limited to university-aged male participants. Future researchers should aim to include a more diverse range of ages and should include female athletes to enhance the generalisability of the findings. Secondly, a more in-depth analysis of the kinetic data, particularly focusing on the power and work involved in completing both the TH and QH tasks, could provide deeper insights into the storage and utilisation of the elastic energy capacity of athletes across hops.

# CHAPTER 8: MASTERCLASS: ARE YOU GETTING THE MOST OUT OF YOUR TRIPLE HOP TESTING?

This chapter comprises the following paper published in Physical Therapy in Sport.

**Reference:**

Sharp, A.P., Neville, J., & Cronin, J.B. (2025). Masterclass: Are You Getting the Most Out of Your Triple Hop Testing? *Physical Therapy in Sport.*

## 8.0 Prelude

At this point in the thesis, it was believed that each chapter contained interesting and new information that needed to be organised and integrated into educational resources tailored for practitioners. Chapter 8 summarises the thesis findings and places them in a context aimed at improving physiotherapy practice by deepening understanding of the insights that multiple hop testing can offer and providing information on the implementation of available technology to achieve these goals.

## 8.1 Introduction

A structured and systematic rehabilitation process is critical for facilitating a successful RTS process following injury [41, 152]. Such a process should restore physical capabilities and foster athlete confidence to resume pre-injury levels of competition. Moreover, for athletes in environments with access to pre-injury musculoskeletal screening, this information should be utilised to inform effective RTS strategies and to set the criteria for late-stage rehabilitation testing, with an aim of reaching pre-injury physical performance measures [39, 94]. To achieve this, consideration for RTS protocols must incorporate a comprehensive assessment of factors, including prior injury history, current functional capacity and future needs analysis, sport-specific risk exposure, and psychosocial readiness [6, 8, 28]. Within the domain of lower limb injuries, RTS frameworks have predominantly focused on rehabilitation following ACLR [13, 92], meniscal injuries[43], and hamstring strains [100, 158]. This emphasis is attributable primarily to the high incidence of these injuries and their significant impact on training continuity and return to competitive participation [6], as well as the prevalence of re-injury [96].

Criteria-based RTS protocols and decision-making frameworks are designed to reduce risk for individuals returning to pre-injury activities [67, 96], with the risk of re-injury being understood as multifactorial; including time, sex, age, strength deficits, proprioceptive control, and biomechanical changes [60]. These protocols typically incorporate objective assessments of muscular strength, tests for neuromuscular control (e.g., single leg hop for distance, triple cross-over hop, TH, 6 m timed hop) [67, 96], as well as subjective assessments through qualitative questionnaires to evaluate functional performance and limb symmetry [6, 65, 67, 92, 94]. Achieving a "pass" on RTS assessments has been associated with lower rates of knee injury [67, 96], specifically for secondary ACL injuries [67, 96, 130, 163, 173] and graft ruptures [57, 96]. However, it must be noted that, particularly in ACLR, these reduced rates of re-injury are conflicting in the literature [99, 153, 173] and could also be associated with an elevated risk of ACL injury to the contralateral limb [173].  Of the tests identified in the literature as suitable and frequently used in physiotherapeutic practice for tracking progress and determining clearance for higher-intensity activities such as sprinting and change of direction, the TH test has been shown to be reliable when used with athletic populations [39]. This RTS test serves as the focus of this article.

TH distance is commonly used by clinicians as a key metric to assess lower limb function, with inter-limb comparisons informing the magnitude of symmetry. This is often expressed as the LSI, calculated by comparing the distance achieved by the injured limb relative to the uninjured limb [65, 124]. Researchers however, have questioned the utility of LSI derived solely from hop distance as an adequate indicator of readiness for RTS [64, 165]. Hop distance is the outcome variable and is determined by several biomechanical factors all of which should be evaluated independently where possible. Hop distance may obscure underlying biomechanical deficits, particularly in propulsive and braking force asymmetries [93, 168]. For example, while hop distance LSI values may fall within acceptable thresholds of <15% asymmetry for both re-injury risk and performance [13, 20] (e.g., 97%), Kotsifaki et al. (2022) reported persistent asymmetries in joint contributions during both propulsive (69% symmetry) and braking phases (87% symmetry) of movements in individuals post-ACLR [93]. These findings underscore the importance of incorporating a more comprehensive approach to evaluating jump/hop performance to avoid overlooking clinically relevant compensations.

Hop distance measures alone seem insufficient as standalone criteria to inform RTS decisions following lower limb injuries, and maybe other measures can yield more nuanced insights into athlete RTS. This article aims to provide clinical practitioners with a more in-depth examination of multiple hop testing, outlining its clinical utility, interpretive value, asymmetry, and practical implementation for late-stage RTS. Additionally, the discussion will include recent technological advancements that could be considered during testing that will enhance diagnostic capability across diverse clinical settings and budgetary constraints.

## 8.2 Biomechanics of Horizontal Multiple Hops in Series

### 8.2.1 Triple Hop

Horizontal multiple hops in series consist of a series of unilateral propulsive and braking efforts, showcasing an athlete's capacity for repetitive efforts of single-leg reactive strength. A typical force signal for a TH is shown in Figure 15 with typical force data and outcome measures in Tables 21 and 22. The forces have been delineated into vertical and horizontal forces. Note that the vertical and horizontal forces have been divided further into braking (decelerative or eccentric) and propulsive (accelerative or concentric) forces. The within-braking-phase peak forces are usually classified as landing or impact peaks. Each hop involves a combination of vertical and horizontal propulsive impulses (force x the time over which the force acts), determining take-off velocity and subsequent hop distance. During landing phases, vertical and horizontal braking impulses are generated as the athlete decelerates, stabilises, and repositions the body for the next hop, all while attempting to preserve forward momentum within the limits of their neuromuscular capacity (see Figure 15). This downward decelerative loading is accompanied by stretching or lengthening of the musculotendinous structures and is known as a stretch-load.

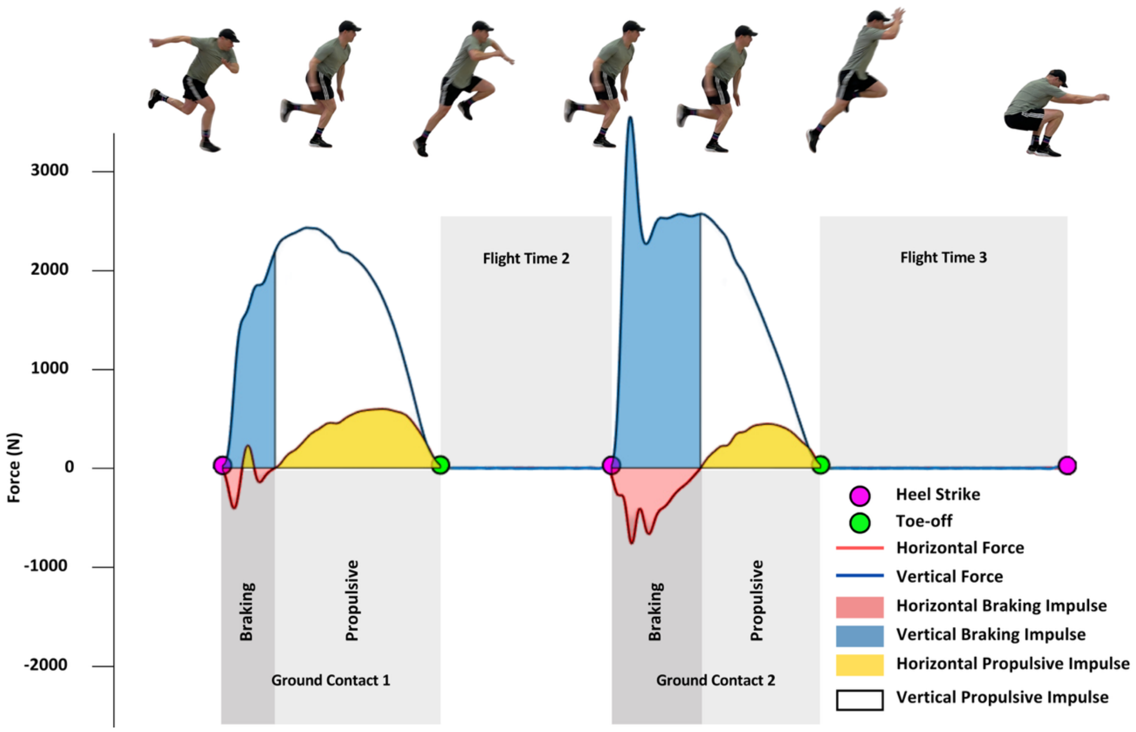


**Figure 15.** The propulsive and braking phases of a TH and associated vertical and horizontal forces

Vertical and horizontal stretch-loads increase with successive jumps due to increased forces (Table 21) over shorter ground contacts (Table 22). The braking phase or landing phase, where significant force dissipation and eccentric rate of force development (RFD) are required, is usually where injured athletes in late-stage RTS can show large functional deficits if not considered in programming [29] and could result in greater risk of exposure to re-injury if not addressed [30]. Insufficient eccentric RFD and dynamic lower limb control, aside from limited exposure to appropriate strength programming, could also result from impaired recruitment of high-threshold motor units due to mechanoreceptor damage, especially after ACLR [28, 29]. Furthermore, the knee extensor muscles are biomechanically disadvantaged because of reduced actin–myosin filament overlap during knee end-range extension, leading to a decreased contribution to maximal knee joint torque [26, 32, 142]. As a result, the knee compensates by relying more heavily on endo- and exo-sarcomeric connective tissues and other passive elastic elements, which might also be in a state of recovery given a longer time course for adaptation post-injury. These increases in stretch-load between the first and second ground contacts of a TH, particularly in vertical (2x) and horizontal (~4x) braking demands, can be seen in Figure 16 and Table 21.

**Table 21.** Example force data during a horizontal TH for vertical and horizontal braking and propulsion phases

| | **Ground Contact 1**<br>**Mean ± SD** | **Ground Contact 2**<br>**Mean ± SD** |
|---|---|---|
| Max Vertical Force (N.kg) | 32.5 ± 4.6 | 42.0 ± 7.60 |
| Vertical Impulse (N.kg) | 5.67 ± 0.44 | 5.87 ± 0.34 |
| Vertical Braking Impulse (Ns.kg) | 1.34 ± 0.63 | 2.58 ± 0.46 |
| Vertical Propulsive Impulse (Ns.kg) | 4.36 ± 0.43 | 3.32 ± 0.48 |
| Horizontal Impulse (N.kg) | 0.70 ± 0.16 | 0.30 ± 0.15 |
| Horizontal Braking Impulse (Ns.kg) | 0.05 ± 0.02 | 0.19 ± 0.05 |
| Horizontal Propulsive Impulse (Ns.kg) | 0.76 ± 0.13 | 0.50 ± 0.11 |

**Table 22.** Example kinematic outcome measures during a horizontal TH

| | **1**<br>**Mean ± SD** | **2**<br>**Mean ± SD** | **3**<br>**Mean ± SD** | **Total**<br>**Mean ± SD** |
|---|---|---|---|---|
| Flight Time (s) | 0.28 ± 0.03 | 0.33 ± 0.04 | 0.44 ± 0.05 | – |
| Ground Contact Time (s) | 0.28 ± 0.03 | 0.26 ± 0.03 | – | – |
| Hop Distance (m) | 1.69 ± 0.15 | 2.03 ± 0.23 | 2.73 ± 0.31 | 6.48 ± 0.63 |
| Reactive Strength Index ($RSI_{horDIST}$) | 7.26 ± 1.39 | 10.71 ± 2.18 | – | 11.99 ± 2.21 |
| Reactive Strength Index ($RSI_{horFT}$) | 1.18 ± 0.25 | 1.72 ± 0.34 | – | 1.44 ± 0.28 |

## 8.2.2 Quintuple Hop

For physiotherapists who have higher-functioning athletes, it is suggested that a QH may provide a means to test the athlete’s ability to tolerate higher stretch-load demands that may be more indicative of sport. Anecdotally, the authors have noted that many athletes exhibit good coordination in TH; however, with higher stretch-loads, for some individuals there is a loss of coordination in hopping rhythm, likely due to inadequate strength to handle such braking forces, which in turn affects the utility of the test. For example, vertical ground reaction force increases by approximately 14% between successive contacts during TH and QH tests, ranging from 3.3x to 5.1x body weight from the first to the fourth ground contact (Figure 16) [151]. With successive hops, the demand on the tissues and structures responsible for vertical eccentric braking forces (plantar-flexors, vasti muscle group) of the lower limbs increases by ~32% to counter the body's downward momentum, while the horizontal braking demand (dorsi-flexors, hamstrings, gluteals) increases by ~56% [151]. This indicates that the foot, during landing, is likely touching down further in front of the line of the CoM, a result of the system's need to produce greater forces to prevent collapse to the ground. The increased percentage contribution of both vertical and horizontal braking contributions to 'net impulse' for both TH and QH with successive contacts can be observed in Figure 17. With the increase in braking demand, there is a decrease in vertical (21-24%) and horizontal (40-57%) propulsive output between the first and last hops, likely due to the body's capacity to produce force during shorter ground contact time, a result of the increased velocity in the body's CoM.

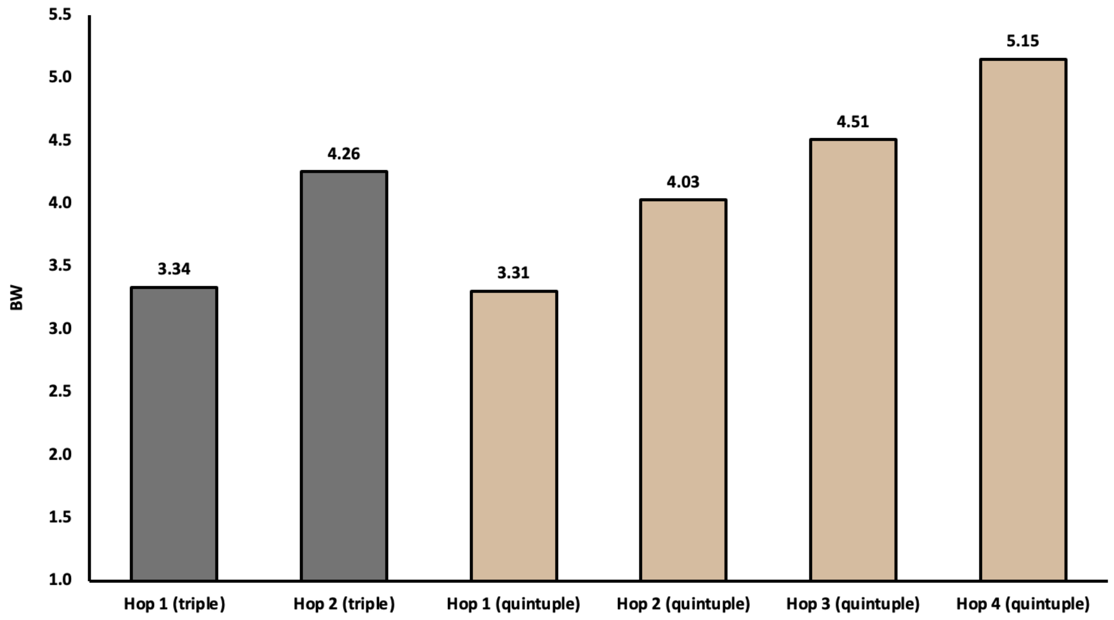


**Figure 16.** Vertical force shown in bodyweight (BW) across hops

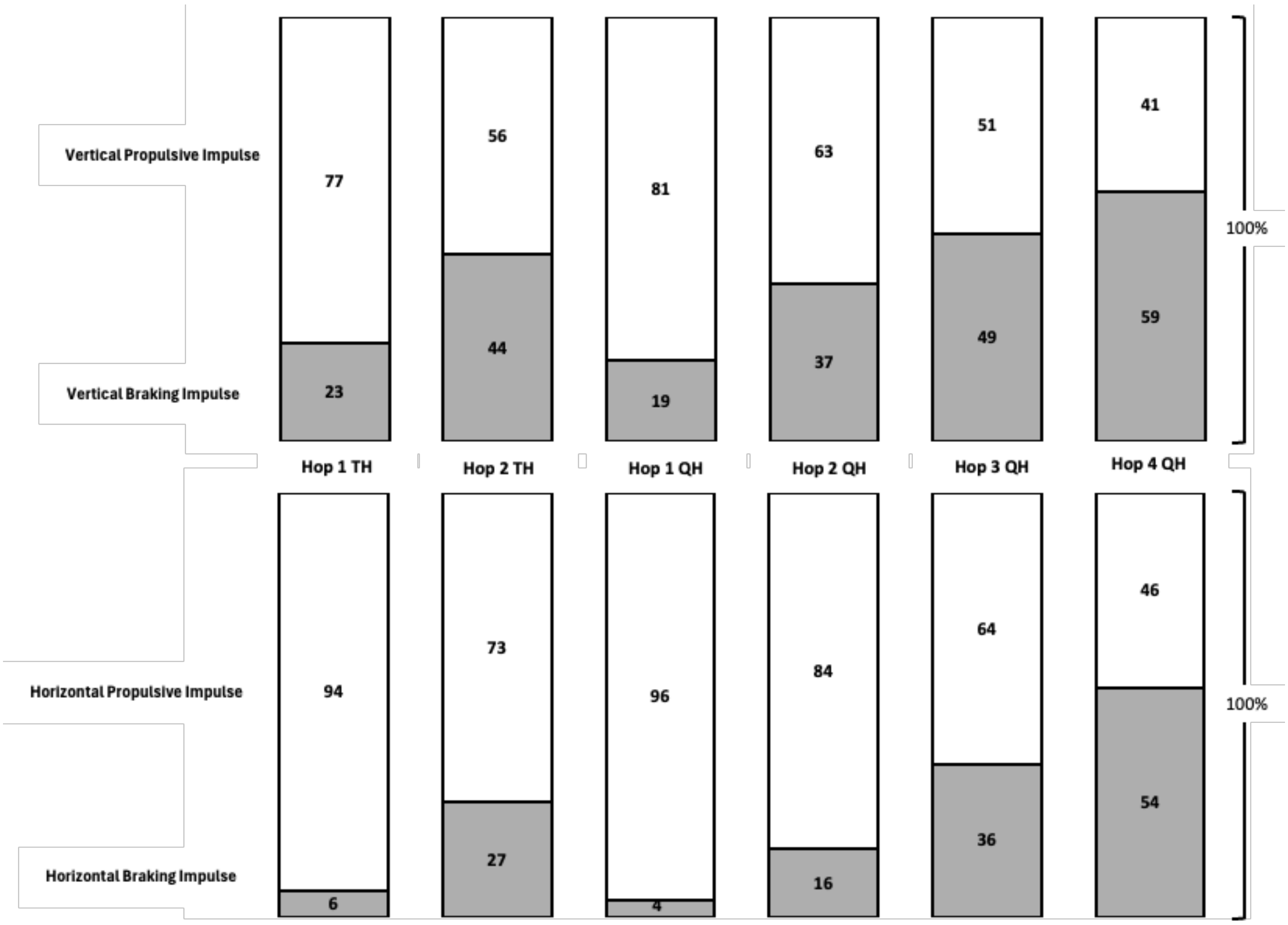


**Figure 17**. Percentage contribution of vertical and braking impulse towards net vertical and anterior-posterior impulse across horizontal multiple hops

### 8.2.3 Asymmetry

Due to the increased stretch-load demands of the QH, the associated elevation in injury risk may be unjustified as a form of RTS assessment. This risk must be considered in the context of the individual's status and functional capacity and the anticipated physical demands of their sport upon return. Figure 18 provides a framework for decision-making specific to the variables of interest and introduces the concept of outcome versus movement strategy variables. The technology required to assess these variables is discussed later in this article. Many RTS protocols emphasise outcome-based metrics, such as hop distance, without considering the underlying movement strategies that influence these outcomes. Key determinants of a movement strategy include the kinetic components of vertical and horizontal braking and propulsive forces/impulses, which affect kinematic factors such as flight duration and ground contact time during each hop, which in turn are affected by the range of motion of the trunk, hip, knee and ankle [47]. A more granular analysis of these kinetic and kinematic factors offers deeper insight into the athlete's functional status and helps identify specific deficits that may need to be addressed to facilitate successful RTS, because as previously highlighted, outcome-based measures like hop distance may not fully capture underlying joint work asymmetries or compensatory movement patterns.

The RSI in the horizontal plane ($RSI_{hor}$), typically calculated as hop distance ($RSI_{horDIST}$) or flight time ($RSI_{horFT}$) divided by ground contact time across multiple hops, has been shown to correlate strongly with sprinting and change-of-direction performance [139, 147] and is a useful variable to assess and monitor. RSI is considered a fundamental determinant of various athletic qualities [82] and, due to its demonstrated reliability, particularly within the context of TH assessments, is a valuable addition to the RTS test battery [44]. Because $RSI_{hor}$ is a function of both flight time and distance (both reflective of propulsive force application) and ground contact time (which encompasses the braking phase, CoM repositioning, and subsequent force generation), it offers a complementary assessment of lower-limb reactive strength than flight time or ground contact time in isolation. Caution is warranted however when interpreting ratio-derived measures such as the RSI, and even more so for LSI, which introduces an additional layer of complexity. To accurately interpret changes in these variables and support evidence-based decision-making, it is essential to also examine their underlying components, such as ground contact time, flight time, and displacement [16].

As can be observed in Figure 18, one of the outcome measures of the TH (usually hop distance) is determined by movement strategies that are essentially a combination of kinetic and kinematic factors. In essence, LSI [124] could be quantified on any number of these measures, depending on the technology available and the focus of the assessment. The LSI compares DOM versus NDOM or affected versus non-affected limbs and is used to determine readiness for RTS and can include assessments of strength, RSI, endurance, change-of-direction/agility, and landing mechanics [40, 57, 65, 124, 172]. The single-leg hop, TH, and crossover hop as common methods for assessing horizontal symmetry [44, 93, 97, 115, 138].

Recent insight from the Aspetar Orthopaedic and Sports Medicine Group challenges the clinical utility of distance-based measures and their associated symmetry indices in assessing biomechanical knee function following ACLR. As previously mentioned, although LSI values for hop distance may indicate acceptable levels of asymmetry (< 15%), individuals after ACLR often continue to show significant imbalances in joint mechanics and particularly during the propulsive phase (with only 69% symmetry) and the braking phase (87% symmetry), even though hop distance LSI was as high at 97% [93]. Notable deficits in knee peak flexion angle (~9%), knee extensor moments (~14%), and increased knee adduction moments (~17%) have been observed in elite runners following ACLR, even after completion of RTS programs and successfully achieving performance test outcomes [3]. Outcome measures such as distance fail to capture joint-specific contributions to movement and do not accurately reflect the functional capacity of the knee joint. Notably, during the propulsive phase of a hop, approximately 10-14% of the work is performed by the knee, with the remaining 88% attributed to the hip and ankle [93]. Sharp et al. (2025) found greater individual asymmetries in kinetic variables, particularly braking impulse asymmetries as high as 95.4% [146], most likely due to differing braking movement strategies and/or eccentric force capability [78], with the greatest asymmetry only 12.7% in hop distance and 9.3% in total hop distance performed. These findings underscore the inadequacy of distance alone as a surrogate for assessing knee function and highlight the need for more joint-specific biomechanical analyses in RTS decision-making [92]. Furthermore, the reader needs to be cognisant that when reviewing the literature, average asymmetry differences across groups can be trivial to small; however, substantial within-group variability in many cases can be observed. Moreover, the direction of asymmetry often fluctuates between individuals, underscoring the need for individualised data analysis rather than reliance on group means alone [44].

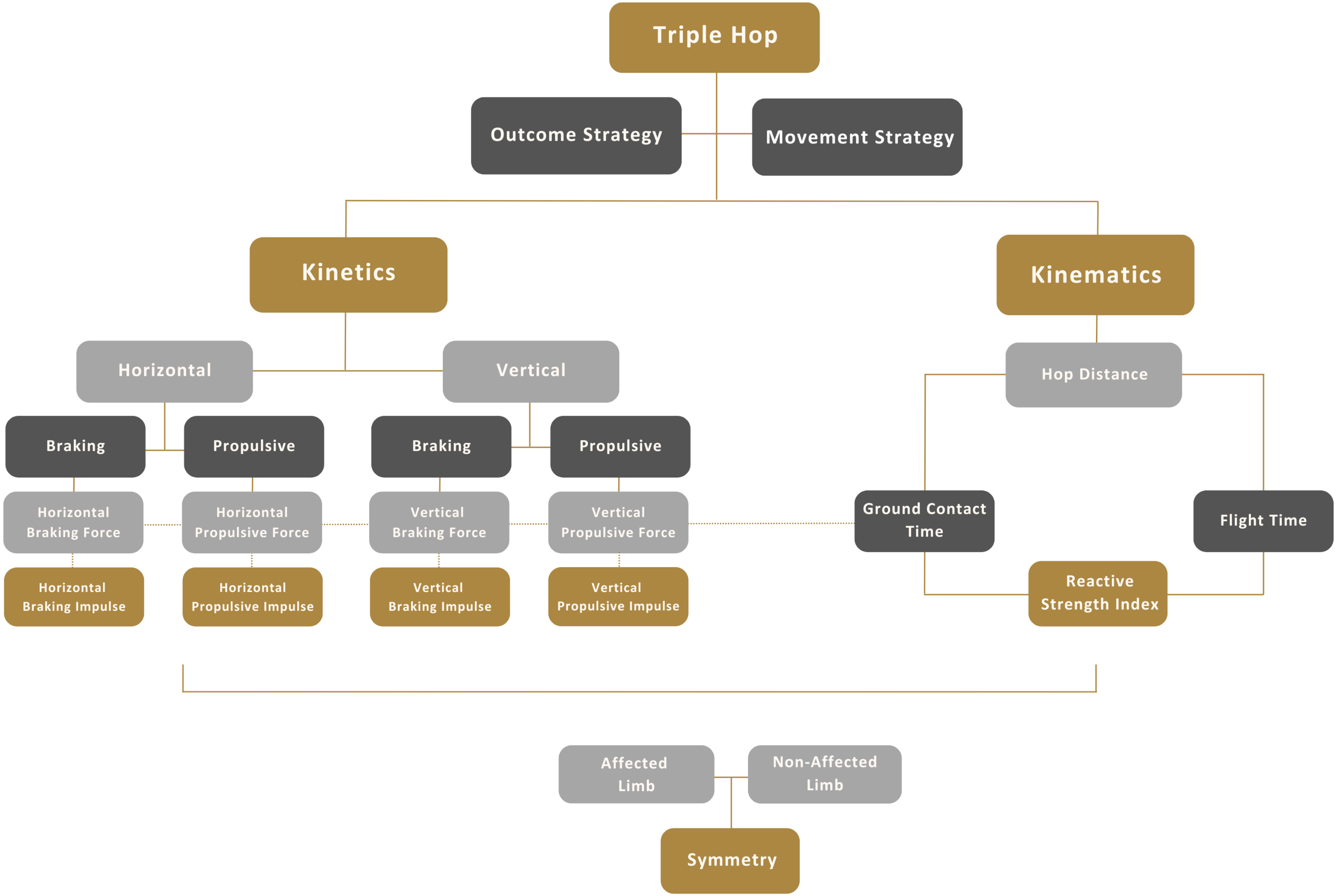


**Figure 18.** Deterministic model of TH performance

### 8.2.4 Technology Integration for Better Diagnostics

The diagnostic information available to practitioners is inherently limited by the technologies accessible within their environments. Many of the advanced measures discussed previously can only be determined in a laboratory setting, such as asymmetry metrics derived from in-ground force platforms, and are often impractical in routine clinical or field settings due to their high cost and substantial infrastructure requirements. To address this limitation, this section introduces technologies that can be used to measure the kinematic and kinetic variables detailed in Figure 18, which should in turn enhance the diagnostic utility of multiple hop testing.

A systematic framework for technology integration, mapping each tool to its diagnostic capabilities, is detailed in Figure 19. The diagram showcases the progression from low-cost tech to “gold standard” options. Increasingly, low-cost technologies are becoming available to practitioners, enabling the collection of meaningful, high-quality data that can inform clinical decision-making.

Tier 1 assessment involves traditional methods for assessing TH performance, such as using a measuring tape. A standardised warm-up and assessment protocol (Appendix IX) ensures consistency and reliability in measurement. The hopping sequence is illustrated in Figure 20. This method allows for the evaluation of overall hop performance via total distance covered, as well as limb symmetry by comparing outcomes between the affected and unaffected limbs.

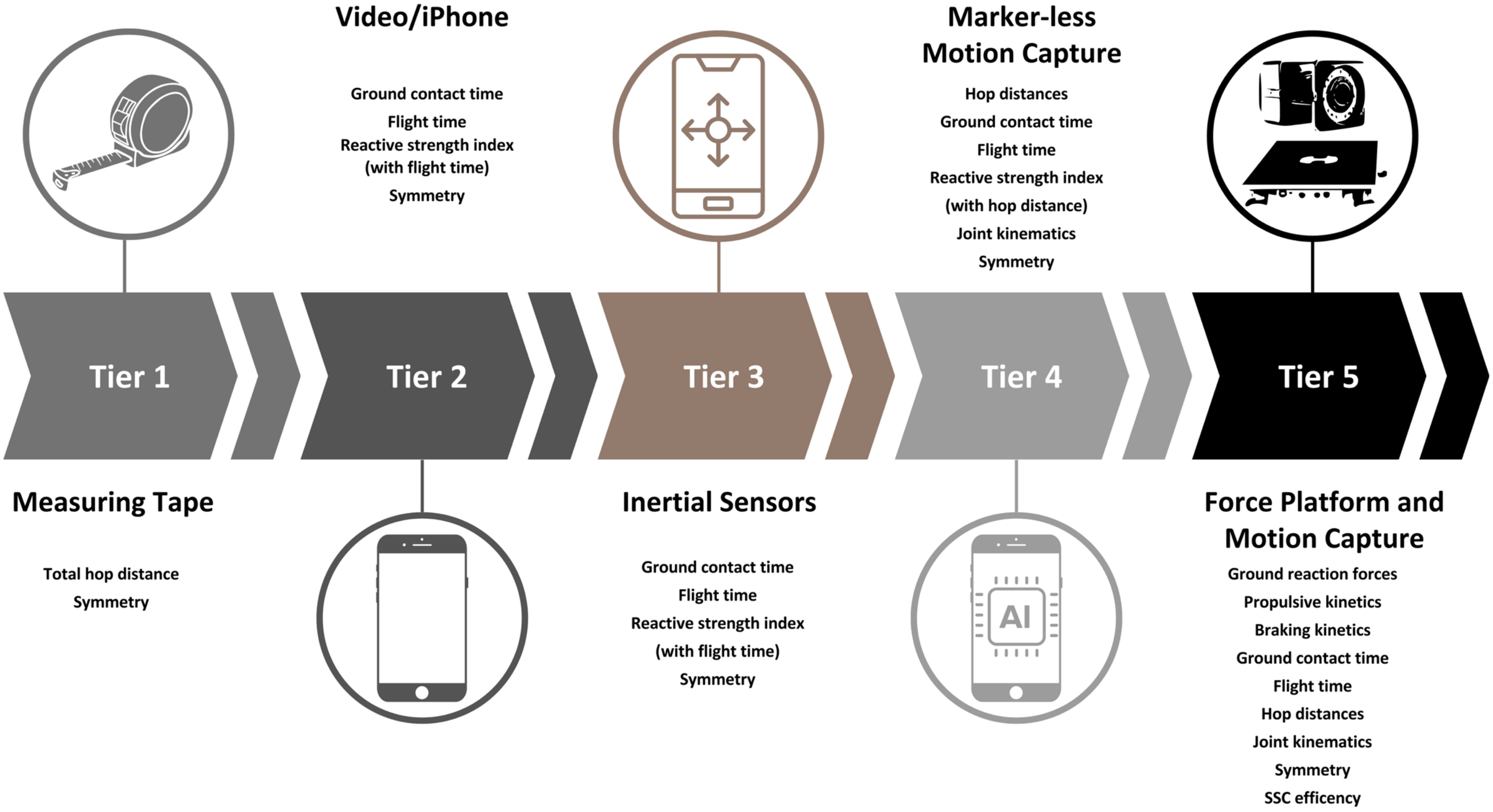


**Figure 19.** Technological options in the assessment of horizontal multiple hops in series

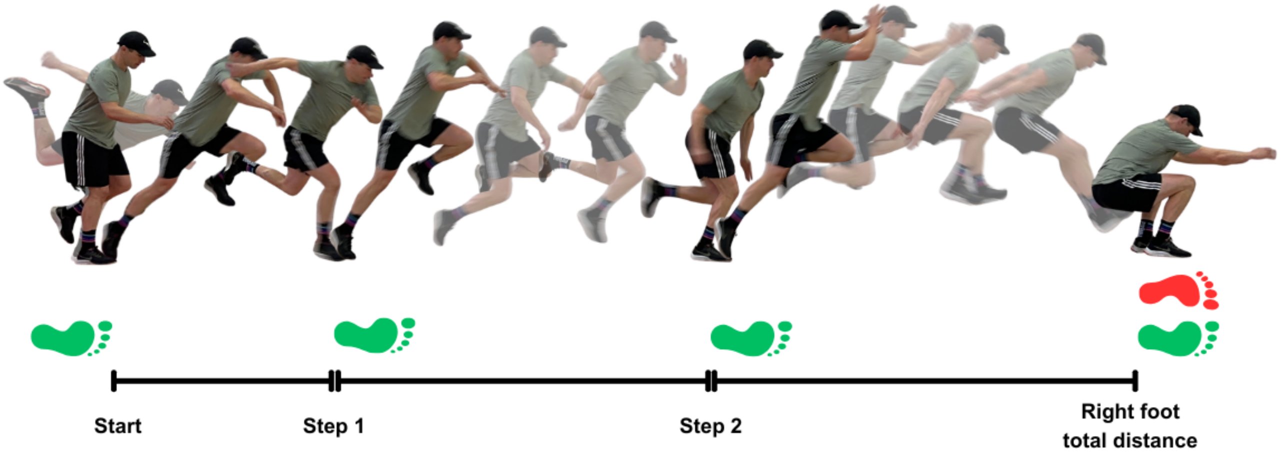


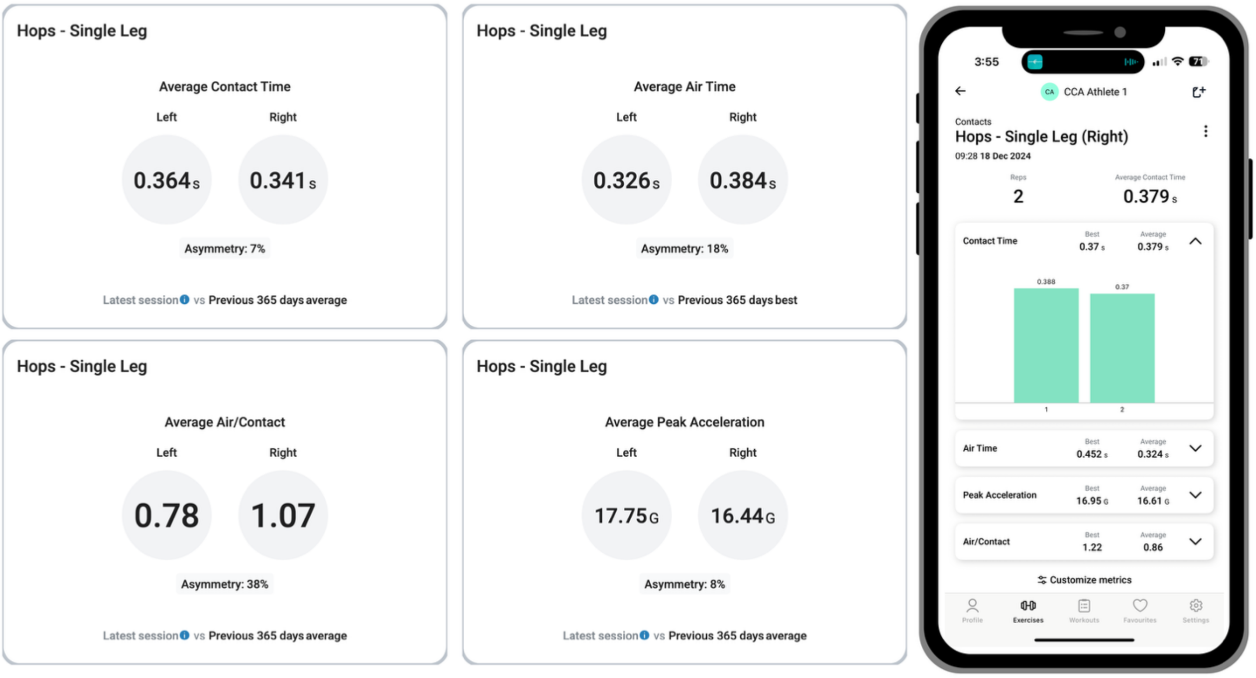
**Figure 20.** The sequence of a right foot TH (green)

Tier 2 assessments incorporate videographic assessment in conjunction with a measuring tape to enhance the evaluation of hop performance. Video-based assessments using a smartphone recording at 120 fps or tablet have been found to be both valid and reliable for TH and QH testing, enabling detailed analysis of each hop phase [149, 150], but with higher frame rates of 240 fps readily available this will likely provide a very high correlation with infrared motion capture in jump detection [11]. For optimal recording, the device should be mounted on a tripod approximately 30 cm above the ground and positioned 14 m from the start line for the TH or 19 m for the QH. Adequate lighting conditions are crucial for accurately detecting key events, such as heel strike and toe-off. The recorded footage can be analysed using open-access motion analysis software, such as Kinovea (https://www.kinovea.org), which has a high level of functionality to measure temporal events (flight and contact times), as well as joint kinematics through manual annotation.

**Figure 21.** Attachment of the IMU sensor to the shoe using a Velcro strap

Tier 3 assessments can provide automated detection of hop kinematics utilising inertial measurement units (IMUs), which present a non-invasive, field-friendly option for assessing the mechanical demands of hopping tasks and have shown to have acceptable levels of reliability when compared to 'gold standard' measurements on force platforms [38]. Several commercially available products such as those at Output Sports (https://www.outputsports.com) utilise IMUs capturing data at 500 Hz, and can be easily attached to the dorsal surface of an athlete's training footwear using a Velcro attachment (see Figure 21) prior to hop assessment, and offer automated measurement of spatiotemporal variables, e.g., ground contact time, flight time, and then RSI is derived, as well as proxy measures of landing impact forces based on acceleration data (see Figure

22). IMUs enable a more nuanced and practical approach to movement assessment in performance and rehabilitation settings. An example of immediate data from a right leg TH, collected using an Output Sports IMU and an iPhone is shown in Figure 22. In this example, key performance metrics including GCT (contact time), FT (Air time), peak acceleration (representing peak deceleration at impact), and RSI (calculated as Air Time/Contact Time), which are generated from a single TH. These variables can be used to assess and monitor changes in both propulsive and braking capabilities over time, as well as to quantify asymmetries between the affected and unaffected limbs. The magnitude of asymmetry from the averaged hop data for the left and right legs is also shown in Figure 22.



Hops - Single Leg

Average Contact Time

Left 0.364 s

Right 0.341 s

Asymmetry: 7%

Latest session vs Previous 365 days average

Hops - Single Leg

Average Air Time

Left 0.326 s

Right 0.384 s

Asymmetry: 18%

Latest session vs Previous 365 days best

Hops - Single Leg

Average Air/Contact

Left 0.78

Right 1.07

Asymmetry: 38%

Latest session vs Previous 365 days average

Hops - Single Leg

Average Peak Acceleration

Left 17.75 G

Right 16.44 G

Asymmetry: 8%

Latest session vs Previous 365 days average

CCA Athlete 1

Contacts

Hops - Single Leg (Right)

09:28 18 Dec 2024

Reps 2

Average Contact Time 0.379 s

Contact Time — Best 0.37 s — Average 0.379 s

Air Time — Best 0.452 s — Average 0.324 s

Peak Acceleration — Best 16.95 G — Average 16.61 G

Air/Contact — Best 1.22 — Average 0.86

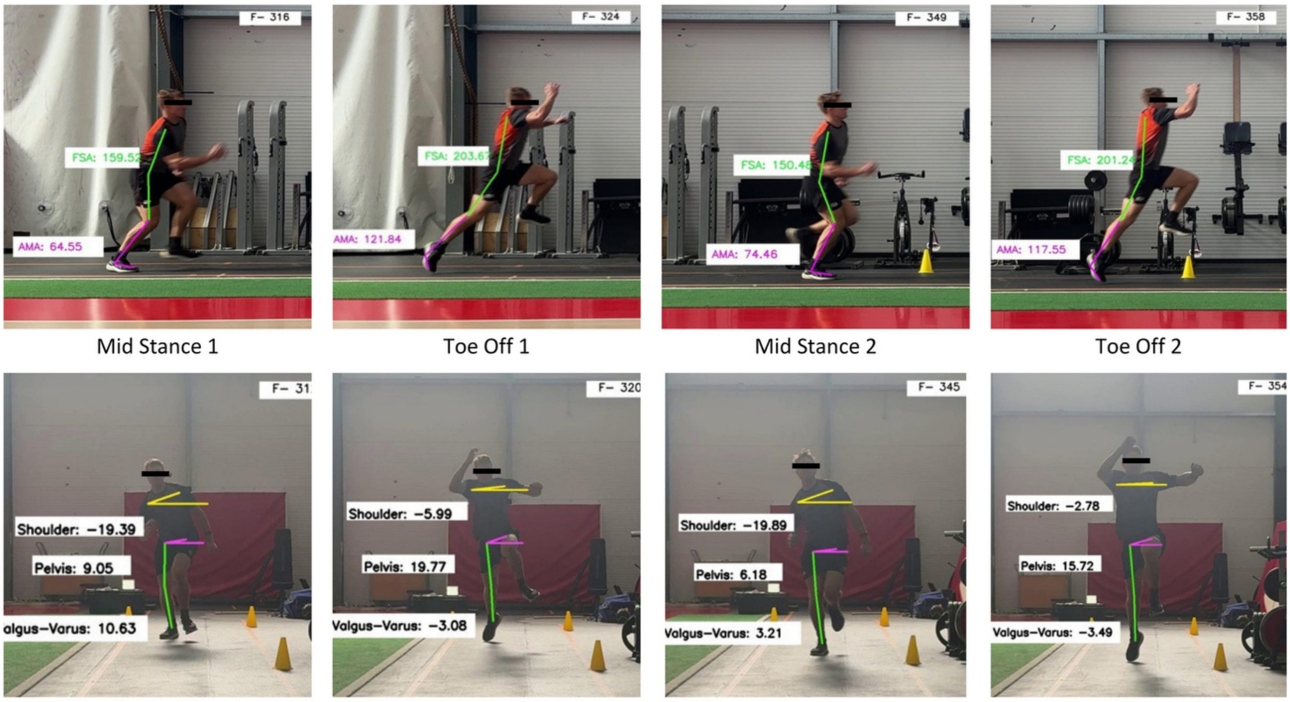
**Figure 22.** TH kinematics and kinetics are automated using a commercialised IMU (Output Sports)

Tier 4 technology offers a more advanced, yet still accessible, solution through the use of 3-D marker-less motion analysis systems and integrated AI based data management, such as VueMotion (https://www.vuemotion.com), which utilise video captured from multiple iPhones. Although further validation is required, preliminary evidence suggests that these systems can provide biomechanical insights comparable to those obtained from traditional marker-based motion capture technologies, but with significantly reduced cost and complexity [140, 157]. VueMotion is an AI-driven video analytics platform capable of generating comprehensive kinematic reports, kinograms, and augmented reality overlays, offering deeper insights into the movement strategies employed during each hop. For dual-plane assessment (frontal and sagittal), three iOS devices are required; two for video capture and one to synchronise the recording process. Once footage is collected, it is uploaded to a server, and detailed reports are typically generated within 24 hours. These reports include a wide range of outcome variables, and kinematic movement strategy variables across key joints, such as the shoulder, spine, pelvis, knee, and ankle, and at critical time points including initial contact, peak knee flexion, and take-off of TH. A small sample of the data is shown in Table 23 and Figure 23. This information is vital for understanding the motor strategies used by affected versus unaffected limbs and can be leveraged to identify key physical capacities for development, as well as to guide coaching and rehabilitation strategies targeting compensatory gait patterns.

**Table 23.** A sample of TH kinematics data captured using a commercialised AI video application (VueMotion)

| | **Left** | **Right** | **Asymmetry (%)** |
|---|---|---|---|
| Total Distance (m) | 6.77 | 7.23 | 6.36 |
| Hop Distance 1 (m) | 2.08 | 1.92 | 8.33 |
| Hop Distance 2 (m) | 2.00 | 2.25 | 11.11 |
| Hop Distance 3 (m) | 2.69 | 3.06 | 12.09 |
| Reactive Strength Index 1 ($RSI_{horDIST}$) | 6.67 | 8.04 | 17.04 |
| Reactive Strength Index 2 ($RSI_{horDIST}$) | 10.76 | 12.24 | 12.09 |
| Flight Time (%) | 58.65 | 61.31 | 4.34 |
| Ground Contact Time (%) | 41.35 | 38.68 | 6.88 |

**Note:** $RSI_{horDIST} = \left(\frac{Hop\ Distance}{Ground\ Contact\ Time}\right)$ measured in $m \cdot s^{-1}$



Mid Stance 1 | Toe Off 1 | Mid Stance 2 | Toe Off 2

**Figure 23.** TH joint kinematics automated using a commercialised AI video application (VueMotion) in sagittal and frontal planes.
**Key:** FSA = femur spine angle; AMA = ankle maximum amortization angle

Tier 5 technology incorporates gold-standard biomechanical assessments using both force platforms and motion capture software, limited to laboratory-based data capture. As such, their application to in-field analysis is not practical for most practitioners, and therefore, the discussion of this technology is outside the scope of this article. Future research could, however, employ force platforms to determine stretch-shortening cycle (SSC) efficiency in cyclical movements in the horizontal direction, such as the TH, thereby building on the work by Pedley et al. (2022) [125]. This could add a further layer to the RTS criteria and drive physical programming, coaching cues, and intent with rehabilitation sessions.

## 8.3 Conclusions

The TH test is a simple, reliable, and effective tool for assessing an athlete's physical status and readiness to return to sport. It can be easily administered with minimal equipment, typically requiring only a tape measure, yet, when combined with accessible and cost-effective technology, it can yield higher-level insights into an athlete's neuromuscular and lower limb function. These tools enable asymmetric assessments on nuanced biomechanical components of RTS, providing insight that can inform targeted rehabilitation strategies and guide future programming to optimise recovery while reducing the risk of re-injury.

# CHAPTER 9: OPTIMISING MULTIPLE HOP TESTING: PRACTICAL INSIGHTS AND PERFORMANCE IMPLICATIONS IN PHYSICAL ASSESSMENT AND TRAINING DESIGN

This chapter comprises the following, submitted to Strength and Conditioning Journal.

**Reference:**

Sharp, A.P., Neville, J., & Cronin, J.B. (2025). Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design. *Under review.*

## 9.0 Prelude

Translating the research findings of the thesis into a cohesive and meaningful resource for physiotherapists was the goal of Chapter 8. Chapter 9 follows the same approach but synthesises previous findings into a context more specific to strength and conditioning practice.

## 9.1 Introduction

The utility of horizontal multiple hop testing in series, including TH and QH, has been described previously [155], as well as their validity and reliability [23, 69, 115, 149, 150]. Horizontal multiple hop assessments, particularly the TH for distance, are commonly employed by sports medicine and physical performance practitioners to evaluate lower limb cyclic force expression and inter-limb asymmetry. The hop distances achieved in these tests are frequently used to inform RTS decisions, with LSI derived from hop distance serving as surrogate markers for readiness to return and risk mitigation. Hop distance, however, represents an outcome measure influenced by multiple biomechanical components, including joint kinematics, kinetics, neuromuscular control, and inter-segmental coordination. Evaluating only distance may obscure understanding the determinants of performance and/or persistent asymmetries, particularly during propulsion and braking phases, which are critical to dynamic joint loading and overall movement quality [93, 168]. For example, although distance-based LSI values may fall within the traditionally accepted threshold of <15% asymmetry [13, 20], substantial deficits may persist in joint-specific contributions. Kotsifaki et al. (2022) demonstrated that individuals post–ACLR exhibited marked asymmetries in joint mechanics, with symmetry indices of only 69% and 87% during the propulsive and braking phases, respectively, despite acceptable hop distance LSIs. It would seem that the validity of using hop distance alone to infer readiness for RTS has been questioned, emphasising that it may not adequately reflect the underlying biomechanical integrity of movement [64, 165]. Furthermore, the utility of extended horizontal hop assessments, such as the QH for distance, remains poorly defined in the context of both performance profiling and asymmetry detection. Given that these tests may impose greater demands on neuromuscular control and fatigue resistance, they hold potential as more sensitive indicators of lower limb function.

Multiple hop assessments can also provide valuable insights into an athlete’s ability to generate high levels of reactive strength and tolerate substantial stretch-load forces, which are characteristic of elite sporting environments. Recent findings by Sharp et al. (2024) highlighted the considerable increase in stretch-load demands associated with multiple hops performed in series [151], and their utility in understanding an athlete’s physical status. This approach is not novel, as both the assessment and its application in training have been discussed in the athletic literature since the 1970s. Notably, Carlo Vittori, renowned Olympic sprint coach of Pietro Mennea, who won the 200 m gold medal at the 1980 Olympic Games and set a world record in the event, integrated multiple hop testing into his methodology. Vittori’s framework for developing and monitoring the "cyclical expression of strength" included TH and QH for distance [162]. He utilised multiple hops to evaluate an athlete’s capacity to produce repeated high-intensity force outputs at progressively faster speeds, interspersed with brief periods of muscular relaxation or inhibition. These multiple hop assessments provided Vittori insight into the coordination between his athletes’ theoretical force capability and their speed expression, offering a diagnostic perspective on the balance between an athlete’s neuromuscular and performance potential. Specifically, Vittori determined that athletes with a capacity to express strength in sprinting should be able to hop approximately 70% further in a QH compared to a TH.

With the aforementioned information in mind, this article aims to provide strength and conditioning coaches with a comprehensive overview of multiple hop testing, with a particular emphasis on quintuple hopping, outlining the practical applications, interpretive value, and role in assessing inter-limb asymmetry. Furthermore, the article explores technological considerations for physical performance testing that enhance diagnostic capabilities while accommodating a range of performance environments and resource constraints. Finally, an example of how to integrate test outcomes into training design to optimise athletic performance is considered.

## 9.2 Biomechanical Demands of Horizontal Multiple Hops in Series

Horizontal multiple hops in series consist of repeated unilateral propulsive and braking actions, showcasing an athlete’s ability to generate high levels of reactive strength and attenuate significant stretch-load forces, whilst repositioning the body to perform the subsequent hop. A typical force-time profile for a QH is shown in Figure 24, with associated force characteristics and outcome metrics presented in Tables 24 and 25. GRFs are typically separated into vertical and horizontal components and further divided into braking (eccentric) and propulsive (concentric) phases. Peak forces during the braking phase are often referred to as landing or impact peaks. Each hop requires the athlete to generate vertical and horizontal propulsive impulses (i.e., the product of force and time), which influence take-off velocity and contribute to hop distance. During each landing, vertical and horizontal braking impulses are produced as the athlete decelerates, stabilises, and repositions the body in preparation for the next hop. This occurs while attempting to preserve forward momentum within the limits of their neuromuscular system. The rapid deceleration or stretch-load during landing also results in lengthening of the musculotendinous unit under tension, and its capacity is essential for effective elastic energy use, contributing to subsequent propulsive actions.

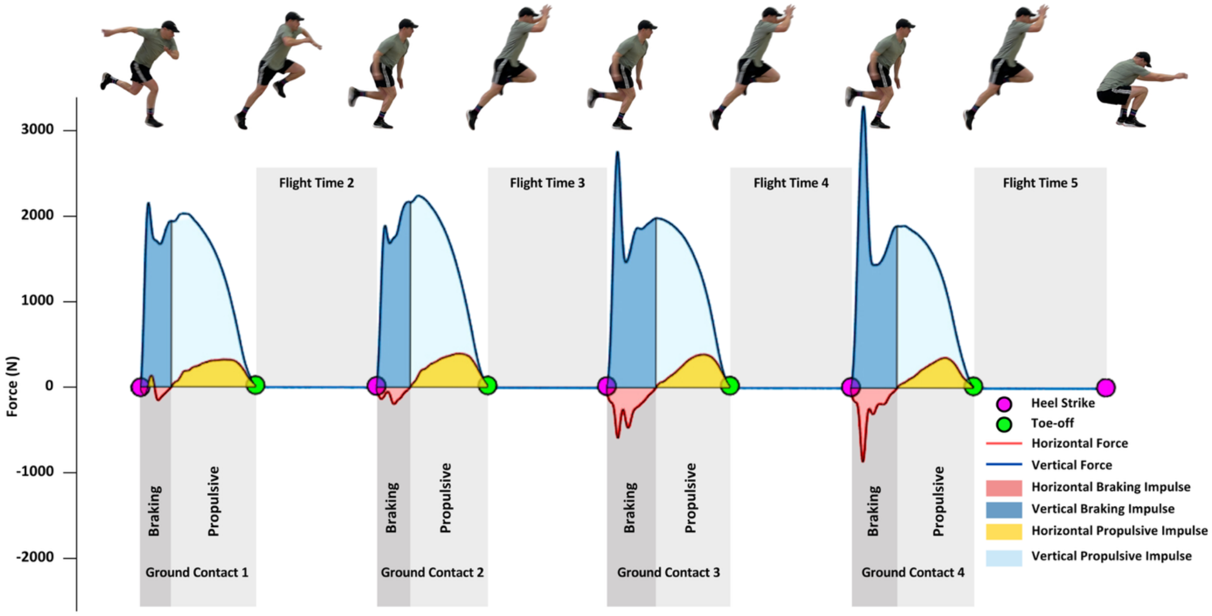


**Figure 24.** The propulsive and braking phases of a QH (four unilateral ground contact phases) with associated vertical and horizontal forces

Vertical and horizontal stretch-loads gradually increase with each hop due to rising forces (Table 24) occurring over shorter ground contact times (Table 25). Notably, the transition from the first to the fourth ground contact in a QH result in substantial increases in stretch-load demands, especially in vertical (~3.5x) and horizontal (~13x) braking, as shown in Table 24. These heightened braking demands reflect the greater neuromuscular effort needed to absorb force quickly and prepare for the next propulsion. The authors have observed that many athletes demonstrate good coordination during TH; however, when faced with the higher stretch loads observed in quintuple hops, they often lose control due to insufficient strength to manage such braking forces, which subsequently affects their test performance. For example, vertical ground reaction forces typically rise by 12–24% between consecutive contacts during the hops, increasing from ~3.3 to 5.1x body weight from the first to the fourth ground contact. This gradual increase highlights the growing demand on the lower-limb muscles to withstand and respond to high-magnitude stretch loads in quick succession, as indicated by the peak forces at heel strike impact (Figure 24). This should be considered before using hops in series in both testing and training [146].

**Table 24.** Example kinetic data during a horizontal QH for vertical and horizontal braking and propulsion phases

| | **Ground Contact 1**<br>**Mean ± SD** | **Ground Contact 2**<br>**Mean ± SD** | **Ground Contact 3**<br>**Mean ± SD** | **Ground Contact 4**<br>**Mean ± SD** |
|---|---|---|---|---|
| Max Vertical Force (N.kg) | 32.1 ± 4.22 | 39.7 ± 7.15 | 45.1 ± 8.76 | 50.7 ± 10.5 |
| Vertical Impulse (N.kg) | 5.48 ± 0.44 | 5.48 ± 0.42 | 5.60 ± 0.40 | 5.88 ± 0.34 |
| Vertical Braking Impulse (Ns.kg) | 1.04 ± 0.58 | 2.02 ± 0.37 | 2.80 ± 0.37 | 3.55 ± 0.58 |
| Vertical Propulsive Impulse (Ns.kg) | 4.46 ± 0.40 | 3.51 ± 0.29 | 2.85 ± 0.24 | 2.43 ± 0.51 |
| Horizontal Impulse (N.kg) | 0.78 ± 0.15 | 0.46 ± 0.09 | 0.20 ± 0.09 | -0.05 ± 0.19 |
| Horizontal Braking Impulse (Ns.kg) | 0.03 ± 0.02 | 0.11 ± 0.03 | 0.26 ± 0.04 | 0.40 ± 0.09 |
| Horizontal Propulsive Impulse (Ns.kg) | 0.82 ± 0.14 | 0.58 ± 0.07 | 0.44 ± 0.07 | 0.35 ± 0.10 |

**Table 25.** Example kinematic outcome measures during a horizontal QH

| | **1**<br>**Mean ± SD** | **2**<br>**Mean ± SD** | **3**<br>**Mean ± SD** | **4**<br>**Mean ± SD** | **5**<br>**Mean ± SD** | **Total**<br>**Mean ± SD** |
|---|---|---|---|---|---|---|
| Flight Time (s) | 0.27 ± 0.03 | 0.32 ± 0.04 | 0.33 ± 0.04 | 0.34 ± 0.04 | 0.45 ± 0.06 | – |
| Ground Contact Time (s) | 0.28 ± 0.03 | 0.25 ± 0.02 | 0.24 ± 0.03 | 0.24 ± 0.03 | – | – |
| Hop Distance (m) | 1.63 ± 0.16 | 1.98 ± 0.22 | 2.21 ± 0.25 | 2.35 ± 0.27 | 2.89 ± 0.37 | 11.1 ± 1.22 |
| Reactive Strength Index ($RSI_{horDIST}$) | 7.30 ± 1.29 | 9.12 ± 1.69 | 9.94 ± 2.03 | 12.2 ± 2.82 | - | 11.2 ± 2.02 |
| Reactive Strength Index ($RSI_{horFT}$) | 1.17 ± 0.23 | 1.36 ± 0.27 | 1.46 ± 0.31 | 1.89 ± 0.43 | - | 11.2 ± 2.02 |

**Note:** $RSI_{horDIST} = \left(\frac{\boldsymbol{Hop\ Distance}}{\boldsymbol{Ground\ Contact\ Time}}\right)$ measured in $m \cdot s^{-1}$

With each successive hop, the mechanical load on lower-limb tissues responsible for vertical eccentric braking, mainly the plantar flexors and the Vasti muscle group increases by ~27–94% to counteract the downward momentum of the centre of mass (CoM). Similarly, the horizontal braking demands on the dorsiflexors, hamstrings, and gluteals rise significantly, by ~54 - 266%. These increases suggest that at heel strike, the foot likely lands further in front of the CoM in successive hops, driven by the need to generate higher braking forces over more extended periods to prevent collapse and sustain forward motion. The growing contribution of both vertical and horizontal braking impulses to the net impulse across successive contacts in the QH can be observed in Figure 25. Along with this rise in braking demands, there is a corresponding decrease in propulsive output. Vertical propulsive impulse drops by around 15 - 21%, and horizontal propulsive impulse declines by 20 - 29% from the first to the last hop. This reduction is probably due to shorter ground contact times and the increasing velocity of the CoM (which results in high stretch-load), limiting the time available to generate force effectively.

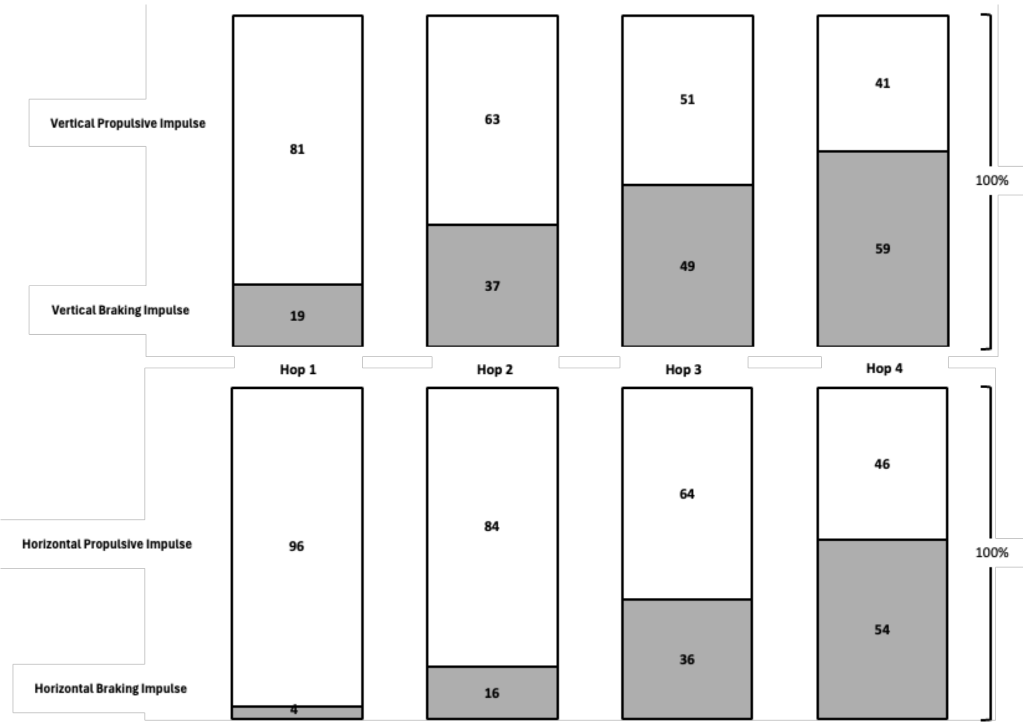


**Figure 25.** Percentage contribution of vertical and braking impulse towards net vertical and anterior-posterior impulse across horizontal QH

### 9.2.1 Reactive Strength Index

Reactive strength refers to the capacity to effectively transition between eccentric and concentric muscle actions, known as the stretch-shortening cycle (SSC). It has received significant attention as a key factor in various athletic abilities [82] and is closely linked to vertical leg-spring stiffness [86]. Reactive strength is typically expressed as RSI, which is calculated as the ratio of jump height to ground contact time during a drop jump [59], or as $RSI_{mod}$, which uses the ratio of jump height to time to take-off in a CMJ [53] or the flight time-to-contact time ratio, sometimes called the reactive strength ratio [34, 73, 97]. Considering the principle of specificity, it may be more appropriate to assess RSI in the direction of movement that is most relevant to the activity. For sprinting, this has led to the development of a horizontal RSI ($RSI_{hor}$) that better captures the demands of horizontal force expression.

The RSI in the horizontal plane ($RSI_{hor}$), typically calculated as hop distance ($RSI_{horDIST}$) or flight time ($RSI_{horFT}$) divided by ground contact time across multiple hops, has been shown to correlate strongly with sprinting and change-of-direction performance [139, 147] and is regarded as a key determinant of numerous athletic performance qualities [82]. Within the context of TH assessments, RSI has demonstrated a high correlation with vertical leg-spring stiffness, an important quality in force transmission and elastic energy return [86]. The RSI offers a complementary measure of lower-limb performance in assessments; however, caution is recommended when interpreting ratio-based metrics. Accurate interpretation and decision making require considering changes in the underlying components, including ground contact time, flight time, and/or displacement [16]. RSI is derived from both flight time and jump distance, variables indicative of propulsive force application, as well as ground contact time, which reflects the braking phase, CoM repositioning, and subsequent force production. Thus, it integrates key components of SSC function into a single, interpretable metric. With the progressive increase in stretch-load demands across successive hops, and particularly during the final two hops of a quintuple hop, the ability to sustain a higher $RSI_{hor}$ becomes more strongly associated with sprint performance [147]. As demonstrated in Table 26, increased $RSI_{hor}$ at Steps 4–5 (calculated using hop distance rather than flight time) accounts for approximately 45% of the variance in 40 m sprint performance in a group of forty-four male university athletes from a wide range of sports disciplines and expertise from novice to elite; including kendo, baseball, rowing, athletics, windsurfing, cycling, soccer, and basketball. Notably, the strength of this relationship increases with distance from the start, underscoring the growing importance of horizontal reactive strength at later stages of the sprint.

**Table 26.** Coefficient of determination ($R^2$) indicating the proportion of variance that Hop RSI explains sprint performance in QH

| | **RSI Mean ± SD** | **5 m $R^2$ Value** | **10 m $R^2$ Value** | **20 m $R^2$ Value** | **40 m $R^2$ Value** |
|---|---|---|---|---|---|
| Hop 1-2 $RSI_{hor\text{-}DIST}$ | 7.30 ± 1.29 | 0.218 | 0.299 | 0.370 | 0.426 |
| Hop 2-3 $RSI_{hor\text{-}DIST}$ | 9.12 ± 1.69 | 0.205 | 0.300 | 0.393 | 0.450 |
| Hop 3-4 $RSI_{hor\text{-}DIST}$ | 9.94 ± 2.03 | 0.212 | 0.283 | 0.356 | 0.413 |
| Hop 4-5 $RSI_{hor\text{-}DIST}$ | 12.2 ± 2.82 | 0.257 | 0.340 | 0.408 | 0.454 |
| Total $RSI_{hor\text{-}DIST}$ | 11.2 ± 2.02 | 0.153 | 0.232 | 0.296 | 0.356 |

### 9.2.2 Asymmetry

Performance assessment using a unilaterally based hopping task, such as multiple hops, lends itself to the possibility of limb comparison to quantify asymmetry. While asymmetry has been investigated extensively in relation to both injury risk [48] and performance [20, 49, 50, 54, 116], the evidence to suggest that asymmetry impacts performance is not definitive [1, 63].

**Table 27.** Percentage asymmetry scores in QH kinematic and kinetic variables

| **Asymmetry Variable** | **Hop 1 Mean ± SD (range)** | **Hop 2 Mean ± SD (range)** | **Hop 3 Mean ± SD (range)** | **Hop 4 Mean ± SD (range)** | **Hop 5 Mean ± SD (range)** |
|---|---|---|---|---|---|
| Flight Time | 4.63 ± 3.23<br>(0.00 – 12.9) | 6.31 ± 5.94<br>(0.00 – 26.5) | 6.18 ± 4.26<br>(0.00 – 17.1) | 5.24 ± 3.98<br>(0.00 – 17.1) | 4.34 ± 3.64<br>(0.00 – 14.9) |
| Ground Contact Time | 4.77 ± 4.02<br>(0.00 – 17.2) | 5.09 ± 4.02<br>(0.00 – 16.7) | 5.52 ± 4.42<br>(0.00 – 17.9) | 4.58 ± 3.66<br>(0.00 – 14.3) | |
| Hop Distance | 3.66 ± 3.27<br>(0.00 – 12.6) | 3.50 ± 3.16<br>(0.00 – 12.7) | 3.88 ± 2.35<br>(0.40 – 10.1) | 4.01 ± 3.07<br>(0.50 – 10.4) | 4.65 ± 3.19<br>(0.00 – 11.9) |
| $RSI_{hor\text{-}DIST}$ | 5.49 ± 4.86<br>(0.00 – 25.8) | 6.08 ± 5.92<br>(0.13 – 28.9) | 7.07 ± 5.29<br>(0.13 – 25.4) | 7.04 ± 4.56<br>(0.33 – 18.5) | |
| Maximal Vertical Force | 8.06 ± 7.24<br>(0.33 – 30.6) | 10.4 ± 8.88<br>(0.08 – 36.6) | 11.2 ± 8.70<br>(0.96 – 28.3) | 11.5 ± 7.61<br>(0.41 – 29.1) | |
| Vertical Braking Impulse | 39.9 ± 31.6<br>(0.00 – 95.4) | 15.6 ± 12.4<br>(0.78 – 53.8) | 13.5 ± 10.9<br>(0.33 – 40.2) | 11.2 ± 8.96<br>(0.00 – 30.8) | |
| Vertical Propulsive Impulse | 8.93 ± 6.13<br>(0.46 – 27.6) | 7.96 ± 5.44<br>(0.00 – 24.3) | 10.2 ± 7.15<br>(0.32 – 31.0) | 15.4 ± 14.00<br>(0.75 – 61.6) | |
| Horizontal Braking Impulse | 32.4 ± 23.6<br>(0.00 – 87.5) | 36.9 ± 23.6<br>(0.00 – 84.0) | 25.0 ± 14.1<br>(0.00 – 61.3) | 19.9 ± 15.0<br>(1.72 – 51.8) | |
| Horizontal Propulsive Impulse | 10.4 ± 8.91<br>(0.00 – 37.4) | 11.8 ± 8.44<br>(0.00 – 31.7) | 14.4 ± 9.82<br>(0.00 – 42.2) | 17.6 ± 12.3<br>(2.56 – 66.7) | |

The averaged asymmetries from the same group of forty-four male university athletes are detailed in Table 27. As can be observed from the table, when looking at kinematic variables the asymmetries are less than 10%, however, the kinetic asymmetries for the same hops ranged from 7.96 to 36.9%. Particularly noteworthy were the horizontal braking asymmetries across hops (19.9 to 36.9%), indicating a real training need for this cohort of non-injured athletes. It needs to be also recognised, that Sharp et al. (2025) found individual asymmetries during multiple hops in kinetic variables, particularly braking impulse asymmetries as high as 95.4% [146], most likely due to differing braking movement strategies and/or eccentric force capability [78], whilst asymmetries of only 12.7% in hop distance were seen. This finding reinforces the importance of taking an individual approach to asymmetry in movement strategy to understand the determinants and asymmetries associated with outcome measures such as hop distance. The key determinants of a movement strategy include the kinetic components of vertical and horizontal braking and propulsive forces/impulses, which affect kinematic factors such as flight duration and ground contact time during each hop. These factors, in turn, are influenced by the range of motion of the trunk, hip, knee, and ankle [47]. A more granular analysis of these kinetic and kinematic factors provides deeper and more nuanced insight into the athlete's functional status. It helps identify specific deficits that may need to be addressed to improve performance, because, as previously noted, outcome-based measures like hop distance might not fully capture underlying joint work asymmetries or compensatory movement patterns. Furthermore, the reader needs to be aware that when reviewing the literature, average asymmetry differences across groups can be trivial to small; however, substantial within-group/individual variability is often observed in many cases. Moreover, the magnitude and direction of asymmetry often fluctuates between individuals, trials, and sessions, underscoring the need for individualized data analysis rather than relying on group means alone [17, 44].

## 9.3 What to Assess and How to Evaluate: Integrating Technology for Improved Diagnostics

A decision-making framework focused on the key performance variables important for hop assessments is shown in Figure 26. Critical factors for developing an effective movement strategy to maximise hop performance include kinetic and kinematic factors. Strength and conditioning coaches need to find ways to measure the various kinetic and kinematic determinants, as the assessment used will predicate the level of insight into an athlete’s functional performance and athleticism. Furthermore, such a layered analysis, can help identify specific neuromuscular deficits and targeted interventions to improve performance.

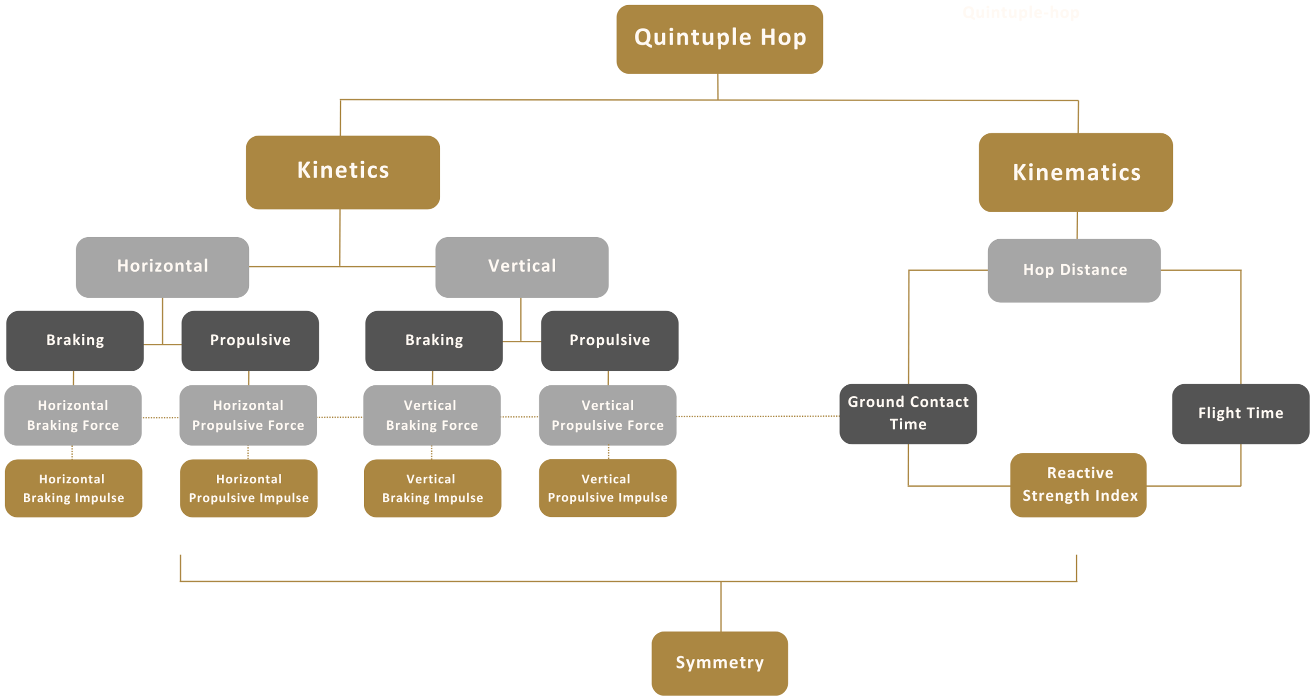


**Figure 26.** Variables of interest in the assessment of QH

In practice, the ability to gather detailed diagnostic information is often limited by the technology available in the weight training room or field settings. Many of the advanced measures discussed earlier, especially those related to asymmetry, have traditionally relied on in-ground force platforms. While these systems offer data of high value, their cost and setup requirements make them unrealistic for most day-to-day environments. To help bridge this gap, the following section highlights a practical tier-based framework that can be used to assess key kinematic and kinetic variables (see Figure 27). These tools can improve the usefulness of multiple hop testing by making it more accessible and applicable in field settings.

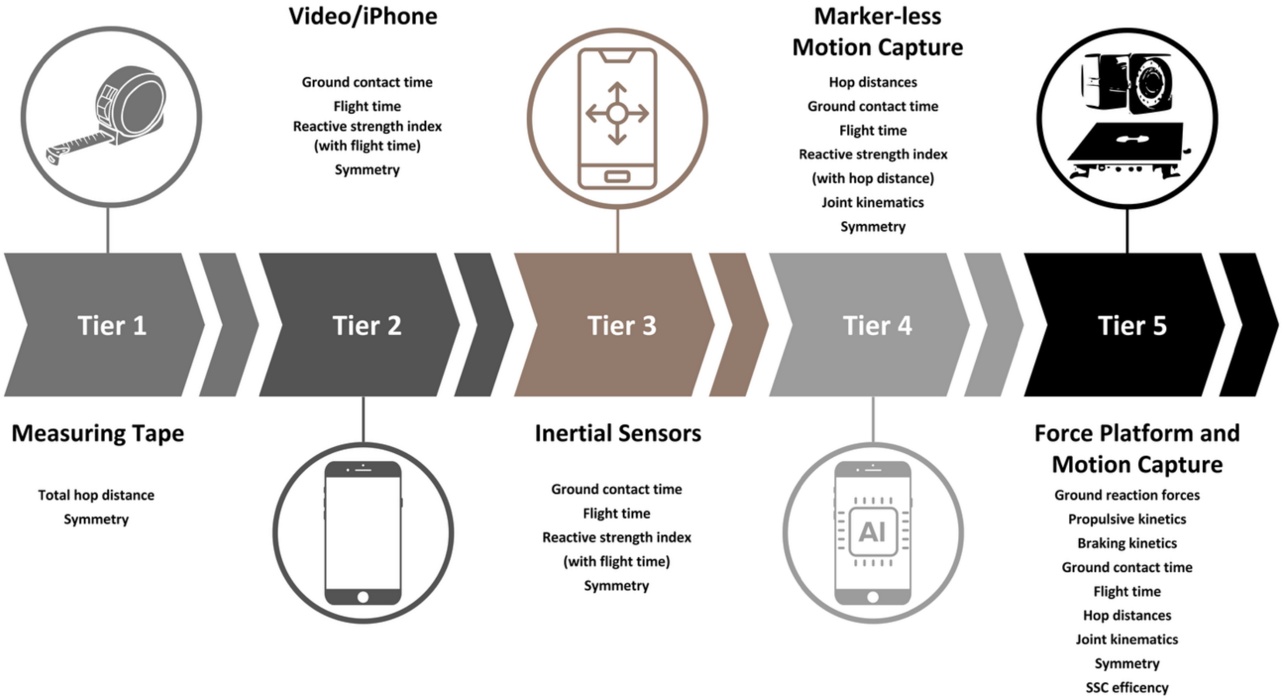


**Figure 27.** Technological options in the assessment of horizontal multiple hops in series

Tier 1 assessment use simple, field-friendly tool like a tape measure to evaluate quintuple hop performance. A standardised warm-up and testing protocol (outlined in Appendix VIII) helps ensure consistent and reliable results. As shown in Figure 28, the hopping sequence allows coaches and athletes to assess total distance covered as a marker of overall hop capacity. It also provides a practical way to examine limb asymmetries by comparing performance between the DOM and NDOM limbs.

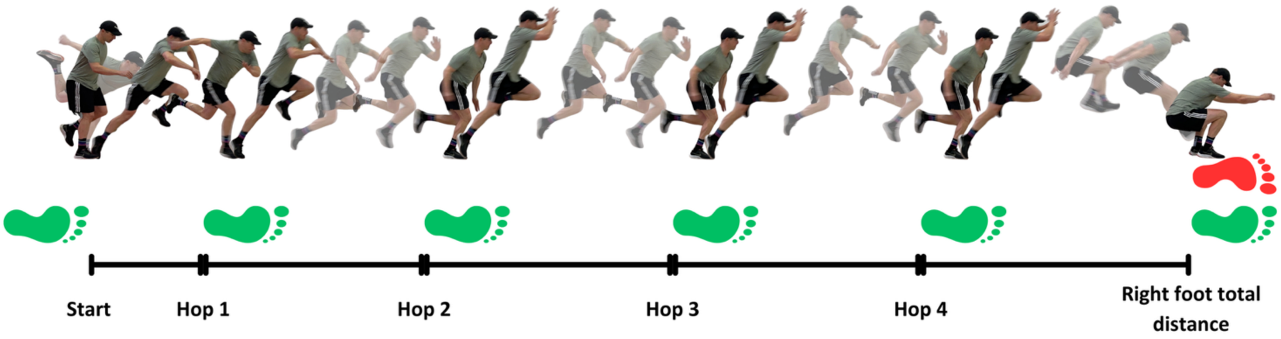


**Figure 28.** The sequence of a right foot QH test (green)

Tier 2 assessments build on the previous method by incorporating video analysis alongside tape measurement to gain deeper insight into hop performance. High-speed video captured using a smartphone or tablet at 120 fps has shown strong validity and reliability for assessing TH and QH performance [149, 150]. Devices capable of 240 fps, now widely accessible, may offer even stronger agreement with gold-standard infrared motion capture for detecting key events like take-off and landing [11]. For best results, the recording device should be placed on a tripod approximately 30 cm off the ground, positioned 19 m from the start line for the QH. Ensuring good lighting is essential for capturing critical movement phases such as heel strike and toe-off. Videos can be reviewed using free software like Kinovea (https://www.kinovea.org), which allows for precise timing analysis (e.g., flight and contact times) and basic joint kinematics through manual annotation [150].

In Tier 3 assessments, automated hop kinematics analysis using IMUs can be used, offering a non-invasive and field-friendly option for evaluating the mechanical demands of hopping tasks. IMUs have been shown to provide reliable data when compared to gold-standard force platforms [38]. Commercial systems like Output Sports (https://www.outputsports.com) offer IMUs that capture data at 500 Hz and can be easily attached to the front of an athlete's training shoe with Velcro (see Figure 29) before starting the hop assessment. This technology allows for real-time measurement of key spatiotemporal variables such as ground contact time, flight time, and RSI, along with estimated landing impact forces based on acceleration data (see Figures 30 and 31). By offering both immediate feedback, IMUs can provide a more detailed and accessible approach to movement analysis in both performance and rehabilitation settings. Example data from left and right limb QH (collected using an Output Sports IMU and iPhone) are shown in Figure 31. Key metrics like ground contact time, flight time, peak acceleration (reflecting peak deceleration at impact), RSI (calculated as Air Time/Contact Time), and drive index (calculated as Contact Time/Air Time) are displayed.

These variables allow practitioners to track propulsive and braking performance, monitor changes over time, and detect any asymmetries between the DOM and NDOM limbs.

**Figure 29.** Attachment of the IMU sensor to the shoe using a Velcro strap

Hops - Single Leg

Average Contact Time

Left 0.424s | Right 0.438s

Asymmetry: 3%

Hops - Single Leg

Average Air Time

Left 0.229s | Right 0.243s

Asymmetry: 6%

Hops - Single Leg

Average Air/Contact

Left 0.5 | Right 0.54

Asymmetry: 8%

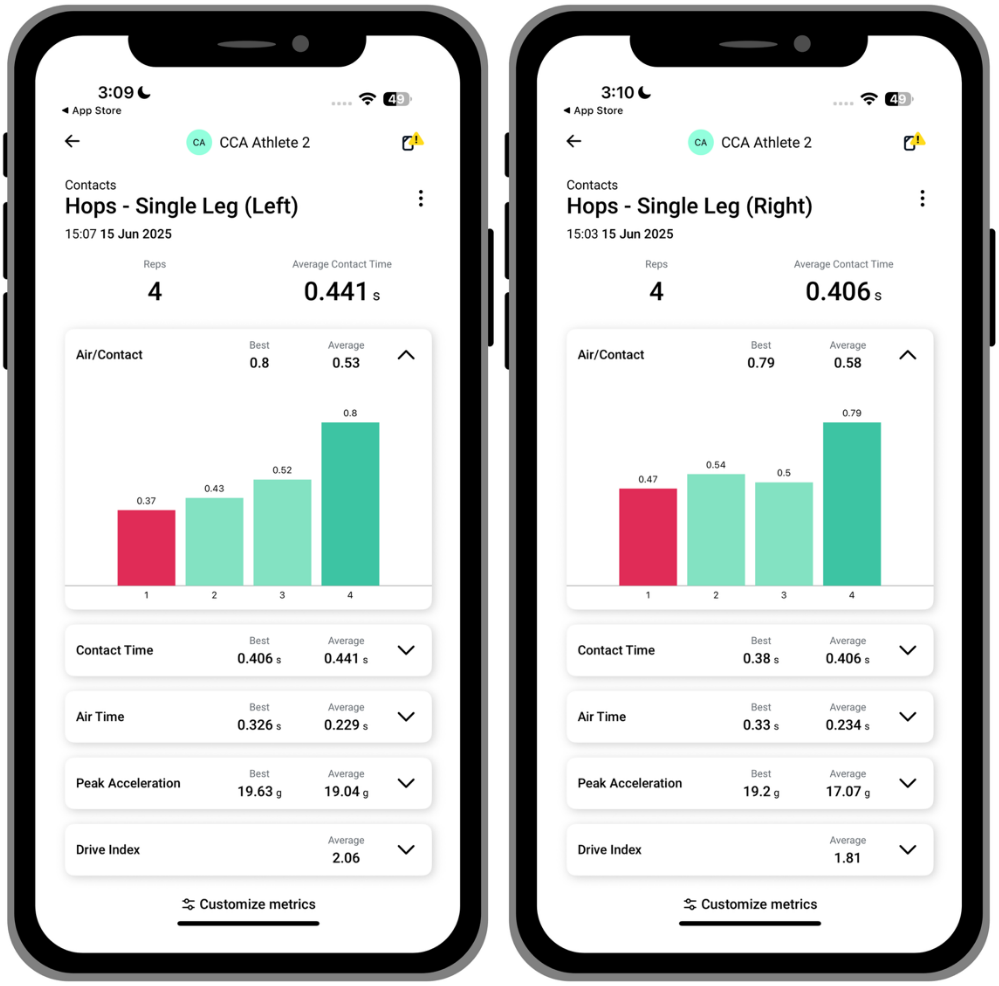
Hops - Single Leg

Average Peak Acceleration

Left 20.02G | Right 17.22G

Asymmetry: 16%

**Figure 30.** Quintuple hop kinematics automated using a commercialised IMU (Output Sports)



CCA Athlete 2

Contacts

Hops - Single Leg (Left)

15:07 15 Jun 2025

Reps: 4 | Average Contact Time: 0.441 s

| | Best | Average |
|---|---|---|
| Air/Contact | 0.8 | 0.53 |
| Contact Time | 0.406 s | 0.441 s |
| Air Time | 0.326 s | 0.229 s |
| Peak Acceleration | 19.63 g | 19.04 g |
| Drive Index | | 2.06 |

CCA Athlete 2

Contacts

Hops - Single Leg (Right)

15:03 15 Jun 2025

Reps: 4 | Average Contact Time: 0.406 s

| | Best | Average |
|---|---|---|
| Air/Contact | 0.79 | 0.58 |
| Contact Time | 0.38 s | 0.406 s |
| Air Time | 0.33 s | 0.234 s |
| Peak Acceleration | 19.2 g | 17.07 g |
| Drive Index | | 1.81 |

**Figure 31.** Automated IMU data captured using an iPhone (Output Sports)

Tier 4 technology presents a more advanced yet practical solution through markerless 3-D motion analysis and AI-powered data processing. Systems like VueMotion (https://www.vuemotion.com) utilise video captured from multiple iPhones to deliver detailed biomechanical insights, eliminating the need for complex or expensive motion capture setups. While additional validation is ongoing, early research suggests these systems can produce data comparable to traditional marker-based methods, but at a fraction of the cost and logistical burden [140, 157]. VueMotion uses AI to automatically generate detailed reports that include kinematic data called kinograms and augmented reality overlays, giving coaches a deeper understanding of movement strategies used during each hop. For dual-plane analysis (frontal and sagittal views), three iOS devices are needed: two for video capture and one for synchronisation. After recording, footage is uploaded to a secure server, and detailed movement reports are typically returned within 24 hours. These reports (see Figure 32) include joint-level data for key segments such as the shoulder, spine, pelvis, knee, and ankle at critical phases like initial contact, peak knee flexion, and take-off during TH. This level of detail helps coaches compare the movement strategies between limbs, identify areas for targeted development, and guide coaching or remedial interventions to address compensatory patterns.

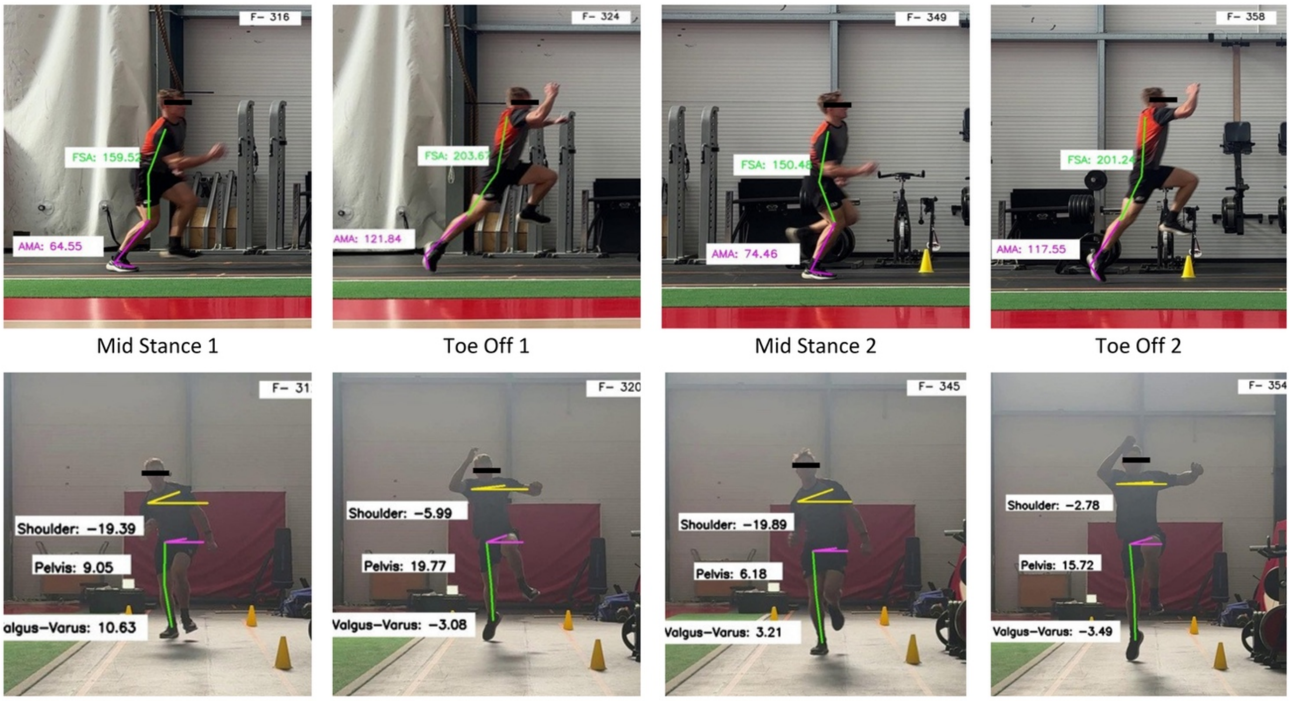


**Figure 32.** QH joint kinematics automated using a commercialised AI video application (VueMotion) in sagittal and frontal planes.
**Key:** FSA = femur spine angle; AMA = ankle maximum amortization angle.

Tier 5 technology represents the gold standard in biomechanical assessment, combining force platforms with motion capture systems. While these tools offer the highest level of precision and detail, they are generally restricted to laboratory environments due to their cost, complexity, and lack of portability. As a result, their use in field-based settings is limited, and they fall outside the practical scope of this article.

## 9.4 Practical Examples

The utility of the TH and QH tests has been discussed throughout this paper. The model presented in Figure 26 identifies the key kinematic and kinetic determinants of hop performance. This model offers a conceptual framework for understanding the primary drivers of performance, thereby informing both assessment strategies and exercise prescription aimed at optimising performance gains. Furthermore, it provides a basis for assessing asymmetry, which can enhance the effectiveness of RTS design. An example of translating hop assessment findings into targeted exercise prescription is illustrated in Figure 33. In the Asymmetry section, asymmetries related to kinetic movement strategy variables were found to be greater than those observed in kinematic measures; accordingly, these kinetic variables form the primary focus of the discussion in this section.

The example illustrated in Figure 33 addresses horizontal and/or vertical braking and propulsive force deficits. Diagnostic findings may indicate impaired braking energy storage or absorption, commonly associated with insufficient eccentric strength and suboptimal stiffness or compliance at specific joints. Training strategies through design and specificity of exercise selection can target the passive elastic components of eccentric force production (e.g., tendon, mysial tissues, etc.) by training the musculotendinous tissues at long muscle lengths to induce adequate stress and strain for tissue adaptation. Methods such as isometric holds, pause training, and eccentric quasi-isometric training at long muscle lengths are well-suited to initiate mechano-transduction.

Eccentric braking capability may also be limited by deficiencies in the active contractile (muscular) components. In cases where vertical and/or horizontal eccentric force capability or asymmetry is identified as problematic, force-vector specific training becomes essential. Examples of vertically oriented eccentric exercises include vertical drop landings, vertical flywheel training, and accentuated eccentric loading. Conversely, when assessments reveal horizontal eccentric force deficits or asymmetries, exercises such as horizontal drop landings or step-outs, horizontal flywheel training, and multiple hop dead stops may be more appropriate.

When addressing propulsive forces and optimising the utilisation of energy stored during the eccentric phase, it is advisable to focus on concentric force capability if testing reveals deficits or asymmetries in propulsive force production. Similar to the braking phase, the propulsive phase can be subdivided into vertical and horizontal components, and training interventions should be tailored to the individual's specific requirements. For improving vertical propulsive force, appropriate exercises include overcoming isometrics, concentric-only lifts, concentric-only ballistic movements, and step jumps in the vertical plane. Conversely, to enhance horizontal propulsive force, suitable options include horizontal overcoming isometrics, concentric sled pushes or towing, and concentric-only horizontal jumps, ensuring specificity to the desired movement pattern.

## 9.5 Conclusions

The QH test presents a simple, reliable, and effective method for evaluating an athlete's physical status, which can be easily administered with minimal equipment, typically requiring only a measuring tape. When integrated with accessible and cost-effective technologies, however, they can provide more comprehensive insights into neuromuscular strengths and deficits to inform training decisions. The QH imposes significantly greater stretch loads on the musculoskeletal system than multiple hop assessments of fewer repetitions, thereby offering superior diagnostic value for athletes who must perform tasks demanding high levels of reactive strength. Furthermore, by assessing asymmetries at an individual level, they can provide further consideration for performance enhancement and for reducing the risk of injury through more focused training design.

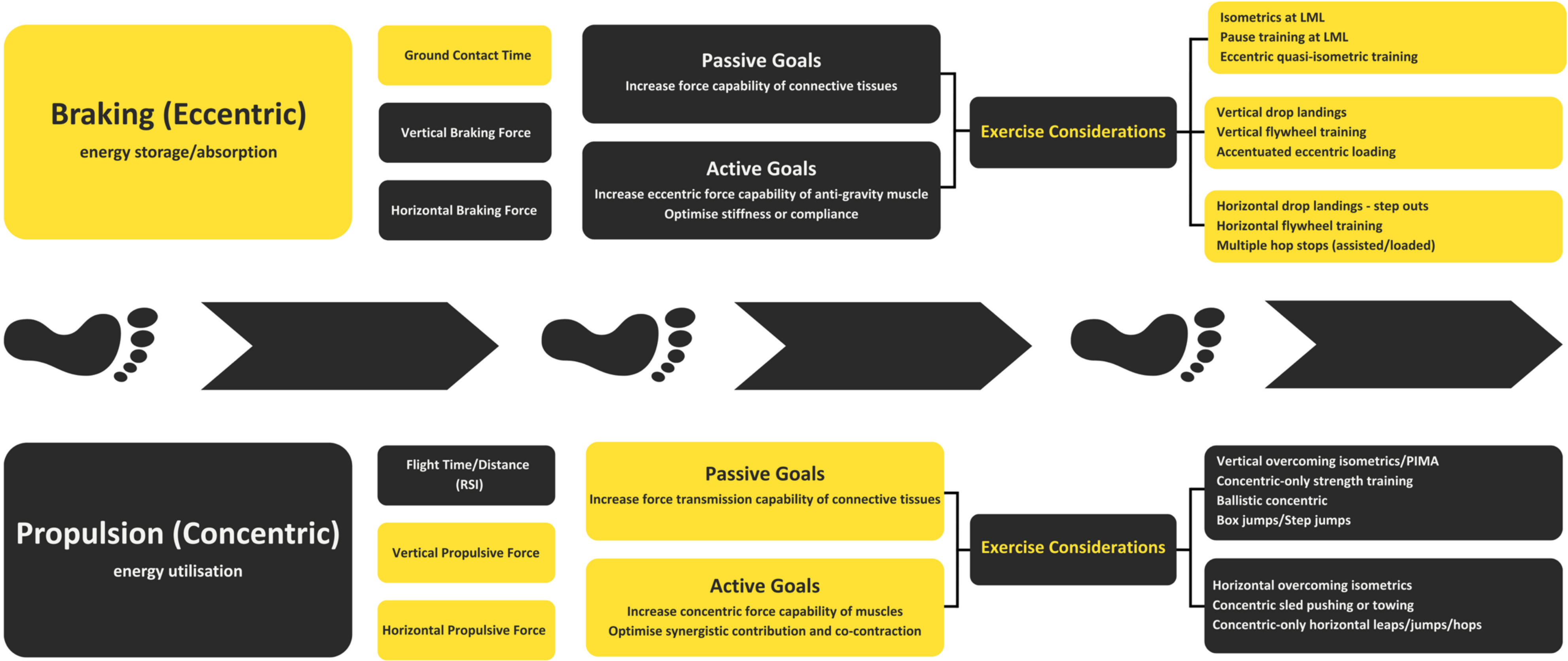
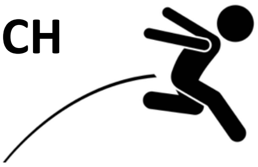


**Figure 33.** Using braking and propulsive components of the hop assessment to inform training prescription
**Key:** LML = long muscle length; AEL = accentuated eccentric loading; RSI = reactive strength index; PIMA = pushing isometric muscle actions; HIMA = holding isometric muscle actions

# CHAPTER 10: SUMMARY AND FUTURE RESEARCH DIRECTIONS



## 10.0 Summary

The overarching question that guided this thesis was, “Can technology integration into multiple hop testing provide greater diagnostic insight to better inform physiotherapeutic and strength and conditioning practices?” To answer this question, several specific research questions were developed.

- What is the current status of the research on TH and QH hops regarding utility, reliability, asymmetry, and their relationship to performance?
- Can smartphone videos offer a valid and reliable way to assess multiple hop variables?
- What are the physical demands of the TH versus QH?
- Do outcome and movement strategy variable asymmetries differ within and between hops?
- Is the performance of multiple hops in series closely related to sprint performance?
- How can the findings uncovered throughout the thesis be translated into a resource that enhances understanding of the usefulness of multiple hop assessments to improve strength, conditioning, and physiotherapy practices?

### Section 1: Where are we at?

The aim of Section 1 was to answer these two research questions:

- What is the status of the research on TH and QH in terms of utility, reliability, asymmetry, and relationship to performance?

- What simple tools can be used to improve the kinematic understanding of multiple hop assessments?

In this section, two chapters were used to understand the current state of the literature on multiple hop testing and identify gaps and limitations that would guide the thesis. Chapter 1 introduced existing research on multiple hops, specifically relating to utility, reliability, asymmetry, and performance, which ultimately determined the thesis direction. The PhD journey began 10 years ago, and the state of knowledge then was very different from today; this has been acknowledged early in the thesis and now. Nonetheless, the main findings were as follows: The TH was commonly used in practice, whereas the use of the QH was less common. However, differences in hop techniques and protocols made comparisons difficult, as a result a need for standardised TH and QH protocols was recommended. The TH was found to have excellent reliability, but the QH had received little scrutiny, suggesting the need for further research, especially in establishing its utility, reliability, validity, and sensitivity. Healthy individuals were found to have TH asymmetries of 10-15%, but the degree of inter-limb asymmetry associated with the QH was unknown. Finally, it was acknowledged that these findings related to total distance jumped, and there was a need to quantify multiple hop performance using methods other than simply measuring distance. This led to the focus of Chapter 2, a literature review exploring the accuracy and sensitivity of smartphone video, as well as its reliability and validity in jump diagnostics.

Quantifying multiple hop performance has largely been limited to measuring total distance jumped. Distance jumped is an outcome measure that offers little insight into the movement strategies involved in hop performance, providing minimal information to improve diagnostics and exercise prescriptions. Simple, accessible technology capable of delivering higher-level information for practitioners was needed. Smartphone technology was one option that met these criteria; however, it was necessary to evaluate the accuracy and sensitivity of smartphone video, as well as their reliability and validity in hop diagnostics. This formed the basis of the Chapter 2 literature review. The main findings of the review were that, as of 2019, there was a clear lack of studies investigating the validity and reliability of smartphone technology for measuring jump or hop performance. At that time, the My Jump App was the only tool available, and it was found to have good validity and reliability across several variables, including jump height, contact time, flight time, and RSI. The app was also extremely easy to use in various settings such as on the court, in the weight room, or on the field, regardless of the iPhone model or user, provided the protocol was followed. However, it should be noted that the data from the My Jump App was based on in-place vertical jumps, and the use of smartphone technology for quantifying cyclic, multiple horizontal hops at that time was unknown.

**Section 2: Keeping it Simple**

The aim of section 2 was to answer this question:

- Can smartphone video provide a valid and reliable assessment of multiple hop variables?

From the previous chapter, it was clear that the smartphone was an easy-to-use technology for quantifying vertical jump performance. Therefore, this section focused on whether this technology could also deliver valid and reliable data on horizontal multiple hop performance. Specifically, in Chapter 3, a tablet and free software (Kinovea) were used to determine the between-rater, within-rater, and test–retest reliability of temporal events, including flight time, ground contact time, and total time during multiple horizontal hop testing. The key findings from Chapter 3 were: (1) good to excellent between-rater consistency for analysis of both DOM and NDOM limbs during the TH and QH tests (ICC = 0.85-1.00), (2) excellent within-rater consistency across all variables in the TH and QH tests (CV = 0.0-2.0%; ICC = 0.98-1.00), and (3) acceptable test–retest relative consistency for all variables (CV = 2.0-8.7%; ICC = 0.47-0.93), with 10 out of 16 variables showing good to excellent consistency over three testing sessions. It was concluded that the low-cost, highly accessible 2-D smartphone/tablet and free software used in this study were reliable in detecting temporal events during multiple hops and could be confidently used by sports performance and rehabilitation professionals.

In Chapter 4, multiple hop kinematics captured via smartphone videography and processed with Kinovea analytic software were compared to data captured on the gold standard in-ground force plates. The main findings of this chapter were that a high level of agreement across all variables of interest was found but were significantly different (flight time; - 0.14 to -5.96 %, ground contact time; 4.89 to 5.83 %, total time; -0.37 to -0.58%). A systematic bias for flight and ground contact times was observed for the TH and QH, which could be statistically corrected. It was concluded the use of iPad and Kinovea software could be used as a valid alternative to measure multiple hop kinematics, when performance coaches do not have access to expensive force-platforms or motion-capture cameras.

### Section 3: Going Deep

The aim of this section was to answer these three questions:

- What are the physical demands of the TH versus QH?
- Do outcome and movement strategy variable asymmetries differ within and between hops?
- Is the performance of multiple hops in series closely related to sprint performance?

Prior to this section, the focus was on finding a simple and cost-effective solution for capturing advanced diagnostics to enable a more detailed understanding and assessment of the kinematics of multiple hop performances. Inter-step and inter-limb comparisons involving flight, contact, and total time, along with total distance, could offer kinematic insights into asymmetry, movement strategies, and outcomes. However, until now, there has been a lack of a kinetic understanding of the hopping movements. This section aimed to address this by providing the reader with a deeper understanding of: the biomechanical (kinematic and kinetic) demands of the TH and QH; the usefulness of these kinematic and kinetic variables in quantifying asymmetry and gaining a better understanding of injury risk; and whether these variables are related to high-level neuromuscular performance (such as sprinting) in non-injured individuals.

The aim of Chapter 5 was to better understand and quantify the kinetic demands of multiple hops in series. Emphasis was placed on determining the increased demands of the QH over the more commonly used TH, as well as the stretch-load demands associated with different hops. The main finding was that with successive hops, there was an average increase of ~32% in hop vertical braking impulses and a ~56% average increase in hop horizontal braking impulses. This suggests a significant and progressive overload to the tissues responsible for vertical and horizontal eccentric braking of the body's downward and forward momentum. The rise in stretch-load demands across hops highlights the importance for practitioners to carefully plan programming to gradually build load tolerance, especially in rehabilitating athletes, to prevent excessive and injurious overload of the lower limb joints and tissues.

Of interest in Chapter 6 was understanding the usefulness of TH and QH kinematics and kinetics in describing vertical and horizontal cyclic asymmetries. Since the higher stretch-loading occurs in the QH, it was thought that greater levels of asymmetry might be detected in the latter hops, i.e., hops 3 and 4. The main findings were as follows: 1) the averaged kinematic asymmetries were below 7.1%, with the greatest asymmetries observed in the QH (hop 2-3) RSI; 2) the average kinetic asymmetries were much higher, < 40.0%, with the largest asymmetries found in vertical braking impulse (hop 1-2); 3) greater asymmetries were observed in horizontal braking (mean = 14.3-38.8%, max = 95.4%) rather than propulsive impulses (mean = 7.77 - 14.8%, max = 66.7%); and, 4) there was considerable individual variability across measures. Ultimately, clinicians and coaches need diagnostic information that improves understanding of an individual's physiological and biomechanical status, which should enable better exercise prescription to enhance patient and athlete outcomes. It appears that asymmetry measured through outcomes like jump distance can mask the extent of some movement strategy asymmetries, which should be considered in future asymmetry assessments.

The thesis examined whether the QH assessment provided more advanced diagnostic information compared to the TH assessment. This was analysed through kinematics, kinetics, and asymmetries in both performance and rehabilitation contexts. From the outset, the utility of hop assessments for profiling, monitoring, and training sprint performance was a key focus. There was limited research on this relationship with the QH hop. Due to the higher stretch-load demands of the QH hop, it was hypothesised that the QH might better differentiate sprinting ability than the TH. Whether this was the case was the focus of Chapter 7. The main findings included: 1) TH and QH distances strongly correlated with 10 m, 20 m, and 40 m sprint times ($r$ = 0.70 to 0.80), while kinetic measures showed weaker to moderate relationships ($r < -0.55$); 2) the association between $RSI_{hor}$ and sprint performance increased with longer sprint distances ($r$ = 0.49 to 0.71; $p < 0.001$), with $RSI_{hor}$ from jump distance being a better predictor than from flight time; 3) hop ratios did not distinguish between fast and slow sprinters, but $RSI_{hor}$ did; 4) significant differences in some kinetic measures for TH and QH tests distinguished fast from slow sprinters; and 5) given the small differences between TH and QH results, including both hops in for sprinting diagnostics may have limited value. These findings provide practitioners with valuable insights into the potential usefulness of multiple hop tests for evaluating and improving athletic performance.

### Section 4: Bringing it Together

The aim of this section was to answer this question:

- How can the findings uncovered throughout the thesis be translated into a resource that enhances understanding of the usefulness of multiple hop assessments to improve strength, conditioning, and physiotherapy practices?

At this stage of the thesis, we believed we had uncovered interesting and novel information in each of the chapters that needed to be organised and integrated into educational resources tailored for practitioners. This step was crucial because research is often not translated into actionable outcomes. Therefore, making the findings “jump” off the paper and into practices that could improve clinical and athletic outcomes was a key consideration. Ultimately, a “Masterclass” approach was adopted to bridge the gap between theory and practice. Chapter 8 synthesised the thesis findings and contextualised them to enhance physiotherapeutic practice by deepening understanding of the insights provided by multiple hop testing and offering guidance on technology implementation to achieve these goals. The aim of Chapter 9 was to translate the thesis research into a cohesive and meaningful resource for strength and conditioning coaches, using a similar approach as Chapter 8. In Chapter 10, the main findings were summarised, practical application of each chapter and limitations discussed, and directions for future research outlined.

## 10.1 Practical Applications

The practical applications of the thesis to enhance the utility of multiple hop assessment for strength and conditioning and physiotherapy became clearer through each chapter and stayed the focus throughout. While Chapters 8 and 9 focus on outlining the practical applications of the thesis, the following applications and recommendations are drawn from Chapters 1 to 7.

**Chapter 2**

1. The use of mobile device videography, specifically with My Jump, was found to have high validity and reliability for key measures such as jump height, flight time, contact time, and RSI.
2. The My Jump app is user-friendly and functional in various settings (court, field, gym) and operates regardless of iPhone model or user, as long as protocols are followed.
3. Strong evidence shows that My Jump and My Jump 2 are effective tools for assessing jump performance across a wide range of populations, from beginner/student athletes to elite athletes.

**Chapter 3**

1. Using a mobile device for videography, along with open-source and free software like Kinovea, provides reliable spatiotemporal data and makes motion analysis both accessible and affordable.
2. Multiple hop tests can be used for performance monitoring to track horizontal explosive ability, fatigue monitoring, and RTS progress in athletes, complementing the more commonly used vertically oriented jump tests.
3. Multiple hop assessments with mobile devices could be especially valuable in telehealth or remote monitoring situations (e.g., when athletes are traveling or rehabbing away from their team), because reliable spatiotemporal data can be collected with portable equipment.
4. The high between-rater reliability means multiple practitioners can analyse the same footage and obtain comparable results, which is useful in team environments or clinical practice.
5. The estimated analysis time of 2–3 minutes per test suggests this method can feasibly be integrated into regular athlete monitoring without significant time costs.

6. By monitoring flight and ground contact times, practitioners can identify suitable training feedback through technical inconsistencies in hopping strategy (e.g., high variability in early hops) and develop targeted interventions.

### Chapter 4

1. The accessibility and affordability of equipment allow coaches and practitioners to use mobile tablets/phones and free software to reliably evaluate multiple hop performance in field settings, making advanced diagnostics more available and cost-effective.
2. Multiple hop tests provide progressive insights into neuromuscular potential, injury risk, movement skills, and performance in both screening and monitoring contexts.
3. A combined assessment of inter-step and inter-limb comparisons of flight, contact, and total time with total distance provides detailed insights into movement strengths and weaknesses.
4. Multiple hops can be used to monitor asymmetry and neuromuscular status during rehabilitation and RTS protocols, as most ground contacts are fast stretch-shortening movements (~0.259 s). These hops are classified as high stretch-load exercises, with forces reaching ~6100 N (≈ 8.9× bodyweight) in a 70 kg athlete within 0.192 s on a single limb.

### Chapter 5

1. The study provides objective reasoning for gradually progressing from TH to QH to avoid excessive overload on athletes in RTP programs, with ~14% increase in maximal vertical forces across successive hops, an increase of ~32% in hop vertical braking impulses, and a ~56% average increase in hop horizontal braking impulses. Carefully implementing a

progressive load as part of programming for rehabilitating athletes is essential to prevent overloading the lower limb and trunk joints and tissues excessively and causing injury.

2. Enhancing an athlete’s ability to resist and quickly reverse vertical eccentric forces should improve propulsive impulse and hop distance.
3. Combining kinetic (strengthening) and kinematic (technique cueing) methods is likely most effective.
4. Practitioners should customise hop assessments and training based on the athlete’s current stretch-load capacity, using kinetic data to inform progression.
5. High variability in horizontal braking impulse indicates individual differences in movement strategies; therefore, personalised analysis and technical coaching are crucial to maximise performance.

**Chapter 6**

1. Multiple hop tests (TH and QH) can help identify subtle asymmetries in braking and propulsion strategies that might not be apparent from hop distance alone.
2. Evaluating both outcome measures (e.g., hop distance) and movement strategy measures (kinetics such as braking/propulsive impulses) offers a more comprehensive understanding of readiness to play or RTS.
3. Large asymmetries in braking impulse indicate that eccentric braking ability should be a major focus in rehabilitation and could also function as a specific screening tool for injury risk.
4. High within- and between-subject variability indicates clinicians should focus on individual tracking rather than relying solely on group averages.
5. Identifying asymmetries in horizontal and vertical components helps improve training to target weaknesses in eccentric braking or propulsive power.

6. Since asymmetry findings were similar in TH and QH tests, coaches might not need to administer both tests, saving time during the testing process.

**Chapter 7**

1. Since hop distances are strongly correlated with sprint times, improvements in multiple hop distances can serve as a surrogate for enhanced sprint ability when timing systems are not accessible.
2. Since the TH provides similar diagnostic utility to the QH but with less stretch-load demand, it may be a better option for athletes early in their rehabilitation. The QH might be better suited for non-injured athletic populations.
3. Hop distances can be monitored along with sprint times, with improvements in hop performance likely indicating significant gains in sprint ability. Multiple hops can serve both as an assessment and a training exercise, with increases in hop distance and $RSI_{hor}$ likely to translate into better sprint performance.
4. $RSI_{hor}$ calculated from jump distance is a better predictor of sprint ability and should be the preferred metric. Flight-time based $RSI_{hor}$ may be used in field contexts when force platforms are unavailable.
5. $RSI_{hor}$ (distance-based) can differentiate between faster and slower sprinters, whereas hop ratios (QH/TH) cannot.

   The development of video-based or AI-powered smartphone apps that can calculate $RSI_{hor\text{-}DIST}$ makes multiple hop assessments feasible outside of laboratory environments.

## 10.2 Limitations

While the research in this thesis has advanced the understanding of multiple hop testing and its diagnostic applications, several limitations should be acknowledged. These limitations provide important context for interpreting the findings and highlight areas where caution is warranted when applying results in practice.

- **Study Design:** Much of the research presented was cross-sectional in nature, meaning results reflect a single point in time rather than changes over training or rehabilitation. As such, the findings provide limited insight into how hop performance and asymmetry develop longitudinally or how they respond to interventions. Additionally, while some studies included short-term test–retest designs, there is a lack of evidence on the stability of measures across weeks or competitive seasons.
- **Participant populations:** The studies involved recreationally active or sub-elite male athletes from a university setting, which may not fully reflect the demands or movement strategies of elite athletes. Additionally, female participants were not included, limiting the ability to make sex-specific conclusions. Lastly, most research was conducted with healthy athletes, providing fewer insights into clinical or rehabilitative populations, thereby restricting direct application to RTS scenarios.
- **Sample size:** The empirical studies did not incorporate an *a priori* sample size calculation to establish statistical power. Instead, the sample comprised a convenience cohort, determined by the maximum number of athletes that could be assessed across a diverse range of sporting disciplines within the 64 available testing sessions.
- **Task specificity:** The thesis examined the TH and QH tests. While these tests offer valuable insights into cyclic propulsion and asymmetry, they do not represent the full range of hopping

tasks used in practical settings, such as lateral hops, crossover hops, or extended sequences beyond the quintuple. This limited focus on specific tasks might reduce generalisation of the findings across different sporting movements.

- **Relationship to performance:** The link between multiple hop and sprint performance was identified, but these results are correlational rather than causal. The predictive value of hop-based variables for a wider range of sport-specific performance outcomes (e.g., agility, change of direction, fatigue monitoring) remains uncertain. Greater insight into the magnitude and direction of asymmetries in TH and QH kinematic and kinetic variables, as presented in Chapter 6, and their relationship with performance outcomes, could have been further explored. Although extreme outlier data were reported, a more detailed examination of these cases and their potential implications for performance would have strengthened the analysis.

  To further explore the relationship between hop and sprint performance, an extreme groups approach was adopted in Chapter 7. Participants were stratified into tertiles based on sprint performance, with comparisons made between the fastest and slowest thirds. This approach is consistent with the principles of ‘extreme groups design’ and was intended to enhance between-group contrast, thereby aiding the detection of potential differences in hop performance characteristics. Focusing on the most distinct performers may improve the clarity of comparisons and support more intuitive interpretation from an applied perspective, particularly when differentiating clearly faster from slower athletes. However, this approach reduces the overall sample size and excludes intermediate performers, which may limit the generalisability of the findings and increase the risk of inflated effect estimates. Furthermore, the omission of the middle tertile may obscure relationships that exist across the full performance continuum. Accordingly, the findings should be interpreted with appropriate caution and considered alongside whole-sample analyses (e.g., correlational or regression-based approaches) to provide a more comprehensive and balanced understanding of the relationship between hop capability and sprint performance.

- **Technology and measurement:** Although smartphone and videographic methods were found valid and reliable, several limitations remain. Systematic biases were identified between video-based measures and force-plate data, and most video analyses relied on manual frame selection, which could introduce rater bias. The studies were deliberately restricted to 2-D frontal plane analysis. This approach was adopted to align with the primary objective of the research, which emphasised the assessment of mechanical output rather than detailed technical movement evaluation. While sagittal plane risk factors such as anterior pelvic tilt, trunk inclination, excessive knee flexion, and limited hip extension are recognised as important factors in the assessment of movement strategies and injury risk, their inclusion was beyond the intended scope of the present work. This methodological decision was driven by a focus on practicality and applicability within field-based settings. Incorporating a more comprehensive, multi-planar analysis may have introduced a level of complexity that detracted from the study's applied focus, particularly given the diverse sporting contexts of the participants. Consequently, while acknowledging the importance of technical movement strategies, the studies prioritised measures that could be reliably and efficiently implemented without compromising ecological validity. Consistency in lighting quality, footwear colour, and camera positioning could influence the clarity of event detection, potentially causing measurement errors in real-world settings without access to LED lighting. The video processing time was not formally measured, though it averaged 2 to 3 minutes per hop. While hop analysis appears efficient, the actual time costs are unknown and require validation before large-scale use. Although emerging technologies like IMUs and AI video analysis were discussed conceptually later in the thesis, they had not yet been fully validated within this thesis.

- **Applied implementation of multiple hops:** The practical insights developed in Chapters 8 and 9 provided translational value for physiotherapists and strength and conditioning coaches. However, these applications were conceptual rather than experimentally tested in applied field settings. As such, while they offer a strong foundation, their effectiveness and feasibility in real-world environments remain to be empirically confirmed.

The limitations of this thesis emphasise the need for caution when generalising findings beyond the specific populations, tasks, and measurement tools studied. Although strong evidence supports the reliability and validity of multiple hop testing, further research is necessary to confirm its longitudinal stability, refine asymmetry thresholds, and validate emerging technology integration across various athletic and clinical settings. These limitations, however, also create opportunities for future research directions, ensuring that subsequent investigations can build on the foundation established in this thesis.

## 10.3 Future Research Directions

- **Technology development and validation:** Integrating automated analysis and event detection, especially with AI-driven video tools and IMUs, presents opportunities for real-time, field-based diagnostics. Further research is then necessary to confirm their reliability across different environments and assessments. To enable meaningful comparisons, the development of standardised protocols would facilitate cross-technology evaluations between smartphones, IMUs, and force platforms.
- **Longitudinal studies:** The long-term stability of hop performance measures across weeks, months, and competitive seasons needs to be determined. Emphasis should be placed on evaluating the sensitivity of these measures to change, especially within rehabilitation contexts

where even minor improvements may hold clinical significance. Furthermore, researchers should also seek to establish minimum detectable changes for key hop variables such as $RSI_{hor}$ and inter-limb asymmetry to support evidence-based decision-making in both clinical and athletic performance settings.

- **Diversity of participation groups:** Including female-only studies to develop female-specific normative data will expand the application and understanding of multiple hops across both sexes. Further insights into elite athletic populations are also vital, as their movement strategies and asymmetry profiles may differ significantly from those of recreational participants. Additionally, examining clinical and rehabilitation populations, such as individuals recovering from ACLR or other lower limb injuries, will help establish hop testing as a reliable part of RTS protocols.
- **Asymmetry and movement strategy:** Longitudinal research is necessary to understand how inter-limb asymmetries might change with training, rehabilitation, and fatigue, and what, if any effect these changes may have on performance. Gaining further insight into the predictive value of asymmetries (kinetic versus kinematic) could provide deeper understanding of injury risk and performance limitations. Additionally, developing individualised thresholds for detecting asymmetry, rather than relying on generic cut-offs (e.g., 10–15%), may improve the accuracy of athlete monitoring and clinical decision-making.
- **Sports-specific performance:** Examining the predictive value of hops and their hop-derived metrics, such as $RSI_{hor}$ and stretch-load tolerance for on-field performance outcomes including sprinting, agility, and change-of-direction speed would further broaden the scope of utility. Additionally, the potential of hop performance as a tool for monitoring athlete readiness or fatigue within training cycles warrants exploration as the proposed TH/QH ratio proposed by Vittori [162] in Chapter 7 was not proven. Finally, the role of hop diagnostics in talent

identification should be assessed, particularly in sports that demand high levels of reactive lower-limb power.

- **Applied training studies:** To improve the practical usefulness of hop testing, future studies should explore how these assessments can be easily integrated into routine training and rehabilitation monitoring systems within real-world team settings. Decision-making models that use hop-based data to inform RTS decisions, adjust training loads, and personalise performance strategies should be thoroughly tested.

## 10.4 Conclusions

This thesis offers original research that enhances the understanding of how multiple hop testing can enhance diagnostic insight into clinical and athletic profiling. From the findings it seems that simple, cost-effective technologies can be effectively incorporated into assessments, providing valid and reliable measures of athlete movement and outcome strategies. While further research is needed to explore long-term applications and practical implementation, this work establishes a clear framework for how such integration can be accomplished in both applied and research settings.

# REFERENCES

1. Afonso J, Peña J, Sá M, Virgile A, García-de-Alcaraz A, and Bishop C. Why Sports Should Embrace Bilateral Asymmetry: A Narrative Review. *Symmetry* 14: 1993, 2022.

2. Akoglu H. User's Guide to Correlation Coefficients. *Turkish Journal of Emergency Medicine* 18: 91–93, 2018.

3. Alarifi SM, Herrington LC, Althomali OW, Alenezi F, Bin Sheeha B, and Jones RK. Biomechanical Analysis after Anterior Cruciate Ligament Reconstruction at the Return-to-Sport Time Point. *Orthopaedic Journal of Sports Medicine* 13: 1–7, 2025.

4. Andrade M, Cohen M, Picarro I, and Silva A. Knee Performance after Anterior Cruciate Ligament Reconstruction. *Isokinetics and Exercise Science* 10: 81–86, 2002.

5. Aoki K, Kohmura Y, Sakuma K, Koshikawa K, and Naito H. Relationships between Field Tests of Power and Athletic Performance in Track and Field Athletes Specializing in Power Events. *International Journal of Sports Science and Coaching* 10: 133–144, 2015.

6. Ardern CL, Glasgow P, Schneiders A, Witvrouw E, Clarsen B, Cools A, Gojanovic B, Griffin S, Khan KM, Moksnes H, Mutch SA, Phillips N, Reurink G, Sadler R, Silbernagel KG, Thorborg K, Wangensteen A, Wilk KE, and Bizzini M. 2016 Consensus Statement on Return to Sport from the First World Congress in Sports Physical Therapy, Bern. *British Journal of Sports Medicine* 50: 853–64, 2016.

7. Atkinson G and Nevill AM. Statistical Methods for Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine* 26: 217–38, 1998.

8. Baez S, Harkey M, Birchmeier T, Triplett A, Collins K, and Kuenze C. Psychological Readiness, Injury-Related Fear, and Persistent Knee Symptoms after Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* 58: 998–1003, 2023.

9. Baker DG and Newton RU. Comparison of Lower Body Strength, Power, Acceleration, Speed, Agility, and Sprint Momentum to Describe and Compare Playing Rank among Professional Rugby League Players. *Journal of Strength and Conditioning Research* 22: 153–8, 2008.

10. Balsalobre-Fernandez C, Glaister M, and Lockey RA. The Validity and Reliability of an iPhone App for Measuring Vertical Jump Performance. *Journal of Sports Sciences* 33: 1574–9, 2015.

11. Balsalobre-Fernandez C, Tejero-Gonzalez CM, del Campo-Vecino J, and Bavaresco N. The Concurrent Validity and Reliability of a Low-Cost, High-Speed Camera-Based Method for Measuring the Flight Time of Vertical Jumps. *Journal of Strength and Conditioning Research* 28: 528–33, 2014.

12. Banda DS, Beitzel MM, Kammerer JD, Salazar I, and Lockie RG. Lower-Body Power Relationships to Linear Speed, Change-of-Direction Speed, and High-Intensity Running Performance in D1 Collegiate Women's Basketball Players. *Journal of Human Kinetics* 68: 223–232, 2019.

13. Barber-Westin SD and Noyes FR. Objective Criteria for Return to Athletics after Anterior Cruciate Ligament Reconstruction and Subsequent Reinjury Rates: A Systematic Review. *The Physician and Sportsmedicine* 39: 100–10, 2011.

14. Belyea BC, Lewis E, Gabor Z, Jackson J, and King DL. Validity and Intrarater Reliability of 2-Dimensional Motion Analysis Using a Handheld Tablet Compared to Traditional 3-Dimensional Motion Analysis. *Journal of Sport Rehabilitation* 24, 2015.

15. Berthoin S, Dupont G, Mary P, and Gerbeaux M. Predicting Sprint Kinematic Parameters from Anaerobic Field Tests in Physical Education Students. *Journal of Strength and Conditioning Research* 15: 75–80, 2001.

16. Bishop C. Using Ratio Data in Strength and Conditioning: Component Parts Hold the Key. *Journal of Strength and Conditioning Research* 39: e176–e179, 2025.

17. Bishop C, Lake J, Loturco I, Papadopoulos K, Turner A, and Read P. Interlimb Asymmetries: The Need for an Individual Approach to Data Analysis. *Journal of Strength and Conditioning Research* 35: 695–701, 2021.

18. Bishop C, Read P, Chavda S, Jarvis P, Brazier J, Bromley T, and Turner A. Magnitude or Direction? Seasonal Variation of Interlimb Asymmetry in Elite Academy Soccer Players. *Journal of Strength and Conditioning Research* 36: 1031–1037, 2022.

19. Bishop C, Read P, Chavda S, Jarvis P, and Turner A. Using Unilateral Strength, Power and Reactive Strength Tests to Detect the Magnitude and Direction of Asymmetry: A Test-Retest Design. *Sports* 7: 58, 2019.

20. Bishop C, Turner A, and Read P. Effects of Inter-Limb Asymmetries on Physical and Sports Performance: A Systematic Review. *Journal of Sports Sciences* 36: 1135–1144, 2018.

21. Bland JM and Altman DG. Measuring Agreement in Method Comparison Studies. *Statistical Methods in Medical Research* 8: 135–60, 1999.

22. Bland JM and Altman DG. Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement. *Lancet* 1: 307–10, 1986.

23. Bolgla LA and Keskula DR. Reliability of Lower Extremity Functional Performance Tests. *Journal of Orthopaedic and Sports Physical Therapy* 26: 138–42, 1997.

24. Bosco C, Luhtanen P, and Komi PV. A Simple Method for Measurement of Mechanical Power in Jumping. *European Journal of Applied Physiology* 50: 273–82, 1983.

25. Brearley S, Wild J, Agar-Newman D, and Cizmic H. How to Monitor Net Plyometric Training Stress: Guidelines for the Coach. *Professional Strength and Conditioning* 47: 15–24, 2017.

26. Bremner CB, Holcomb WR, and Brown CD. Knee Joint Angle Influences Neuromuscular Electrical Stimulation-Induced Torque. *Athletic Training and Sports Health Care* 7: 165–172, 2015.

27. Buchheit M, Samozino P, Glynn JA, Michael BS, Al Haddad H, Mendez-Villanueva A, and Morin JB. Mechanical Determinants of Acceleration and Maximal Sprinting Speed in Highly Trained Young Soccer Players. *Journal of Sports Sciences* 32: 1906–1913, 2014.

28. Buckthorpe M, Gokeler A, Herrington L, Hughes M, Grassi A, Wadey R, Patterson S, Compagnin A, La Rosa G, and Della Villa F. Optimising the Early-Stage Rehabilitation Process Post-ACL Reconstruction. *Sports Medicine* 54: 49–72, 2024.

29. Buckthorpe M, La Rosa G, and Villa FD. Restoring Knee Extensor Strength after Anterior Cruciate Ligament Reconstruction: A Clinical Commentary. *International Journal of Sports Physical Therapy* 14: 159–172, 2019.

30. Buckthorpe M and Roi GS. The Time Has Come to Incorporate a Greater Focus on Rate of Force Development Training in the Sports Injury Rehabilitation Process. *Muscles, Ligaments and Tendons Journal* 7: 435–441, 2017.

31. Carlos-Vivas J, Martin-Martinez JP, Hernandez-Mocholi MA, and Perez-Gomez J. Validation of the iPhone App Using the Force Platform to Estimate Vertical Jump Height. *Journal of Sports Medicine and Physical Fitness* 58: 227–232, 2018.

32. Cavalcante JGT, Marqueti RC, Geremia JM, de Sousa Neto IV, Baroni BM, Silbernagel KG, Bottaro M, Babault N, and Durigan JLQ. The Effect of Quadriceps Muscle Length on Maximum Neuromuscular Electrical Stimulation Evoked Contraction, Muscle Architecture, and Tendon-Aponeurosis Stiffness. *Frontiers in Physiology* 12: 633589, 2021.

33. Cesar GM, Edwards HT, Hasenkamp RM, and Burnfield JM. Prediction of Athletic Performance of Male and Female Athletes Measured by Triple Hop for Distance. *Trends in Sport Sciences* 24: 19–25, 2017.

34. Choukou MA, Laffaye G, and Taiar R. Reliability and Validity of an Accelerometric System for Assessing Vertical Jumping Performance. *Biology of Sport* 31: 55–62, 2014.

35. Chu D and Korchemny R. Sports Performance Series: Sprinting Stride Actions: Analysis and Evaluation. *Strength and Conditioning Journal* 11: 6–9, 1989.

36. Cohen J, *Statistical Power Analysis for the Behavioral Sciences*. 2013, Abingdon: Routledge.

37. Colyer SL, Nagahara R, Takai Y, and Salo AIT. How Sprinters Accelerate Beyond the Velocity Plateau of Soccer Players: Waveform Analysis of Ground Reaction Forces. *Scandinavian Journal of Medicine and Science in Sports* 28: 2527–2535, 2018.

38. Comyns TM, Murphy J, and O'Leary D. Reliability, Usefulness, and Validity of Field-Based Vertical Jump Measuring Devices. *Journal of Strength and Conditioning Research* 37: 1594–1599, 2023.

39. Cooke R, Rushton A, Martin J, Soundy A, Herrington L, and Heneghan NR. Lower Extremity Functional Performance Tests and Their Measurement Properties in Athletes: A Systematic Review and Narrative Synthesis. *BMJ Open Sport and Exercise Medicine* 11: e002389, 2025.

40. Cooper R and Hughes M. *The Melbourne ACL Rehabilitation Guide 2.0*. (https://team-acl.com/melbourne-acl-rehabilitation-guide) 2018.

41. Creighton DW, Shrier I, Shultz R, Meeuwisse WH, and Matheson GO. Return-to-Play in Sport: A Decision-Based Model. *Clinical Journal of Sport Medicine* 20: 379–385, 2010.

42. Cronin JB and Hansen KT. Strength and Power Predictors of Sports Speed. *Journal of Strength and Conditioning Research* 19: 349–57, 2005.

43. Culvenor AG, Girdwood MA, Juhl CB, Patterson BE, Haberfield MJ, Holm PM, Bricca A, Whittaker JL, Roos EM, and Crossley KM. Rehabilitation after Anterior Cruciate Ligament and Meniscal Injuries: A Best-Evidence Synthesis of Systematic Reviews for the Optiknee Consensus. *British Journal of Sports Medicine* 56: 1445–1453, 2022.

44. Davey K, Read P, Coyne J, Jarvis P, Turner A, Brazier J, Šarabon N, Jordan MJ, and Bishop C. An Assessment of the Hopping Strategy and Inter-Limb Asymmetry during the Triple Hop Test: A Test–Retest Pilot Study. *Symmetry* 13: 1890, 2021.

45. Donoghue OA, Shimojo H, and Takagi H. Impact Forces of Plyometric Exercises Performed on Land and in Water. *Sports Health* 3: 303–9, 2011.

46. Dorn TW, Schache AG, and Pandy MG. Muscular Strategy Shift in Human Running: Dependence of Running Speed on Hip and Ankle Muscle Performance. *Journal of Experimental Biology* 215: 1944–56, 2012.

47. Dos Reis AC, Correa JC, Bley AS, Rabelo ND, Fukuda TY, and Lucareli PR. Kinematic and Kinetic Analysis of the Single-Leg Triple Hop Test in Women with and without Patellofemoral Pain. *Journal of Orthopaedic and Sports Physical Therapy* 45: 799–807, 2015.

48. Dos'Santos T, Bishop C, Thomas C, Comfort P, and Jones PA. The Effect of Limb Dominance on Change of Direction Biomechanics: A Systematic Review of Its Importance for Injury Risk. *Physical Therapy in Sport* 37: 179–189, 2019.

49. Dos’Santos T, Thomas C, A. Jones P, and Comfort P. Asymmetries in Single and Triple Hop Are Not Detrimental to Change of Direction Speed. *Journal of Trainology* 6: 35–41, 2017.

50. Dos'Santos T, Thomas C, Jones PA, and Comfort P. Asymmetries in Isometric Force-Time Characteristics Are Not Detrimental to Change of Direction Speed. *Journal of Strength and Conditioning Research* 32: 520–527, 2018.

51. Driller M, Tavares F, McMaster D, and O’Donnell S. Assessing a Smartphone Application to Measure Counter-Movement Jumps in Recreational Athletes. *International Journal of Sports Science and Coaching* 12: 661–664, 2017.

52. Ebben WP, Fauth ML, Garceau LR, and Petushek EJ. Kinetic Quantification of Plyometric Exercise Intensity. *Journal of Strength and Conditioning Research* 25: 3288–98, 2011.

53. Ebben WP and Petushek EJ. Using the Reactive Strength Index Modified to Evaluate Plyometric Performance. *Journal of Strength and Conditioning Research* 24: 1983–7, 2010.

54. Exell T, Irwin G, Gittoes M, and Kerwin D. Strength and Performance Asymmetry during Maximal Velocity Sprint Running. *Scandinavian Journal of Medicine and Science in Sports* 27: 1273–1282, 2017.

55. Exell TA, Irwin G, Gittoes MJ, and Kerwin DG. Implications of Intra-Limb Variability on Asymmetry Analyses. *Journal of Sports Sciences* 30: 403–9, 2012.

56. Ferragut C, Cortadellas J, Arteaga R, and Calbet J. Prediction of Vertical Jump Height. Role of Mechanical Impulse and Leg Muscle Mass. *European Journal of Human Movement* 10, 2003.

57. Figueroa Poblete D, Gonzalez Duque W, Landea Caroca D, Tapia Castillo C, and Erskine Ventura D. Return-to-Sport Tests: Do They Reduce Risk of Re-Rupture after Anterior Cruciate Ligament Reconstruction? *Journal of ISAKOS* 11: 100399, 2025.

58. Fitzgerald GK, Lephart SM, Hwang JH, and Wainner RS. Hop Tests as Predictors of Dynamic Knee Stability. *Journal of Orthopaedic and Sports Physical Therapy* 31: 588–97, 2001.

59. Flanagan EP and Comyns TM. The Use of Contact Time and the Reactive Strength Index to Optimize Fast Stretch-Shortening Cycle Training. *Strength and Conditioning Journal* 30: 32–38, 2008.

60. Fulton J, Wright K, Kelly M, Zebrosky B, Zanis M, Drvol C, and Butler R. Injury Risk Is Altered by Previous Injury: A Systematic Review of the Literature and Presentation of Causative Neuromuscular Factors. *International Journal of Sports Physical Therapy* 9: 583–95, 2014.

61. Gallardo-Fuentes F, Gallardo-Fuentes J, Ramirez-Campillo R, Balsalobre-Fernandez C, Martinez C, Caniuqueo A, Canas R, Banzer W, Loturco I, Nakamura FY, and Izquierdo M. Intersession and Intrasession Reliability and Validity of the My Jump App for Measuring Different Jump Actions in Trained Male and Female Athletes. *Journal of Strength and Conditioning Research* 30: 2049–56, 2016.

62. Garhammer J and Newton H. Applied Video Analysis for Coaches: Weightlifting Examples. *International Journal of Sports Science and Coaching* 8: 581–594, 2013.

63. Girard O. Asymmetry in Sprinting: The Myth of Perfection and the Reality of Performance. *Journal of Sport and Health Science* 14: 101025, 2025.

64. Gokeler A, Welling W, Benjaminse A, Lemmink K, Seil R, and Zaffagnini S. A Critical Analysis of Limb Symmetry Indices of Hop Tests in Athletes after Anterior Cruciate Ligament Reconstruction: A Case Control Study. *Orthopaedics and Traumatology: Surgery and Research* 103: 947–951, 2017.

65. Gokeler A, Welling W, Zaffagnini S, Seil R, and Padua D. Development of a Test Battery to Enhance Safe Return to Sports after Anterior Cruciate Ligament Reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy* 25: 192–199, 2017.

66. Greenhouse SW and Geisser S. On Methods in the Analysis of Profile Data. *Psychometrika* 24: 95–112, 2025.

67. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, and Risberg MA. Simple Decision Rules Can Reduce Reinjury Risk by 84% after ACL Reconstruction: The Delaware-Oslo ACL Cohort Study. *British Journal of Sports Medicine* 50: 804–8, 2016.

68. Habibi A, Shabani M, Rahimi E, Fatemi R, Najafi A, Analoei H, and Hosseini M. Relationship between Jump Test Results and Acceleration Phase of Sprint Performance in National and Regional 100m Sprinters. *Journal of Human Kinetics* 23: 29–35, 2010.

69. Hamilton RT, Shultz SJ, Schmitz RJ, and Perrin DH. Triple-Hop Distance as a Valid Predictor of Lower Limb Strength and Power. *Journal of Athletic Training* 43: 144–51, 2008.

70. Hanney WJ, Kolber MJ, Ramirez MM, Negrete R, Palmer K, Cheatham SW, Pabian P, and Liu X. Csm 2017 Orthopaedic Section Poster Presentations (Abstracts Opo1–Opo243). *Journal of Orthopaedic and Sports Physical Therapy* 47: A58–A161, 2017.

71. Harman EA, Rosenstein MT, Frykman PN, Rosenstein RM, and Kraemer WJ. Estimation of Human Power Output from Vertical Jump. *Journal of Applied Sports Science Research* 5: 116–120, 1991.

72. Haynes T, Bishop C, Antrobus M, and Brazier J. The Validity and Reliability of the My Jump 2 App for Measuring the Reactive Strength Index and Drop Jump Performance. *Journal of Sports Medicine and Physical Fitness* 59: 253–258, 2019.

73. Healy R, Kenny IC, and Harrison AJ. Reactive Strength Index: A Poor Indicator of Reactive Strength? *International Journal of Sports Physiology and Performance* 13: 802–809, 2018.

74. Herrington L, Ghulam H, and Comfort P. Quadriceps Strength and Functional Performance after Anterior Cruciate Ligament Reconstruction in Professional Soccer Players at Time of Return to Sport. *Journal of Strength and Conditioning Research* 35: 769–775, 2021.

75. Holm DJ, Stalbom M, Keogh JW, and Cronin J. Relationship between the Kinetics and Kinematics of a Unilateral Horizontal Drop Jump to Sprint Performance. *Journal of Strength and Conditioning Research* 22: 1589–96, 2008.

76. Hopkins WG. Measures of Reliability in Sports Medicine and Science. *Sports Medicine* 30: 1–15, 2000.

77. Hopkins WG. A Socratic Dialogue on Comparison of Measures. *Sportscience* 14: 15–21, 2010.

78. Hovey S, Wang H, Judge LW, Avedesian JM, and Dickin DC. The Effect of Landing Type on Kinematics and Kinetics during Single-Leg Landings. *Sports Biomechanics* 20: 543–559, 2021.

79. Hunter JP, Marshall RN, and McNair PJ. Relationships between Ground Reaction Force Impulse and Kinematics of Sprint-Running Acceleration. *Journal of Applied Biomechanics* 21: 31–43, 2005.

80. Jales MTM, Barbosa GM, Goncalves GV, Fonseca Fialho HR, Calixtre LB, and Kamonseki DH. Lower Extremity Physical Performance Tests for the Assessment of Athletes Via Telehealth Are Reliable. *Journal of Sport Rehabilitation* 32: 612–616, 2023.

81. Jarvis MM, Graham-Smith P, and Comfort P. A Methodological Approach to Quantifying Plyometric Intensity. *Journal of Strength and Conditioning Research* 30: 2522–32, 2016.

82. Jarvis P, Turner A, Read P, and Bishop C. Reactive Strength Index and Its Associations with Measures of Physical and Sports Performance: A Systematic Review with Meta-Analysis. *Sports Medicine* 52: 301–330, 2022.

83. Kale M, Asci A, Bayrak C, and Acikada C. Relationships among Jumping Performances and Sprint Parameters during Maximum Speed Phase in Sprinters. *Journal of Strength and Conditioning Research* 23: 2272–9, 2009.

84. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe PA, and Bullock MI. A 6-Year Follow-up of the Effect of Graft Site on Strength, Stability, Range of Motion, Function, and Joint Degeneration after Anterior Cruciate Ligament Reconstruction: Patellar Tendon Versus Semitendinosus and Gracilis Tendon Graft. *American Journal of Sports Medicine* 35: 729–39, 2007.

85. King E, Richter C, Franklyn-Miller A, Daniels K, Wadey R, Moran R, and Strike S. Whole-Body Biomechanical Differences between Limbs Exist 9 Months after ACL Reconstruction across Jump/Landing Tasks. *Scandinavian Journal of Medicine and Science in Sports* 28: 2567–2578, 2018.

86. Kipp K, Kiely MT, Giordanelli MD, Malloy PJ, and Geiser CF. Biomechanical Determinants of the Reactive Strength Index during Drop Jumps. *International Journal of Sports Physiology and Performance* 13: 44–49, 2018.

87. Koo TK and Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine* 15: 155–63, 2016.

88. Kossow AJ and Ebben WP. Kinetic Analysis of Horizontal Plyometric Exercise Intensity. *Journal of Strength and Conditioning Research* 32: 1222–1229, 2018.

89. Kotsifaki A, Korakakis V, Graham-Smith P, Sideris V, and Whiteley R. Vertical and Horizontal Hop Performance: Contributions of the Hip, Knee, and Ankle. *Sports Health* 13: 128–135, 2021.

90. Kotsifaki A, Van Rossom S, Whiteley R, Korakakis V, Bahr R, Sideris V, and Jonkers I. Single Leg Vertical Jump Performance Identifies Knee Function Deficits at Return to Sport after ACL Reconstruction in Male Athletes. *British Journal of Sports Medicine* 56: 490–498, 2022.

91. Kotsifaki A, Van Rossom S, Whiteley R, Korakakis V, Bahr R, Sideris V, Smith PG, and Jonkers I. Symmetry in Triple Hop Distance Hides Asymmetries in Knee Function after ACL Reconstruction in Athletes at Return to Sports. *American Journal of Sports Medicine* 50: 441–450, 2022.

92. Kotsifaki A and Whiteley R. Criteria-Based Rehabilitation and Return to Sport Testing after Anterior Cruciate Ligament Reconstruction. *Aspetar Sports Medicine Journal* 12: 60–65, 2023.

93. Kotsifaki A, Whiteley R, Van Rossom S, Korakakis V, Bahr R, Sideris V, Graham-Smith P, and Jonkers I. Single Leg Hop for Distance Symmetry Masks Lower Limb Biomechanics: Time to Discuss Hop Distance as Decision Criterion for Return to Sport after ACL Reconstruction? *British Journal of Sports Medicine* 56: 249–256, 2022.

94. Kotsifaki R, Korakakis V, King E, Barbosa O, Maree D, Pantouveris M, Bjerregaard A, Luomajoki J, Wilhelmsen J, and Whiteley R. Aspetar Clinical Practice Guideline on Rehabilitation after Anterior Cruciate Ligament Reconstruction. *British Journal of Sports Medicine* 57: 500–514, 2023.

95. Kugler F and Janshen L. Body Position Determines Propulsive Forces in Accelerated Running. *Journal of Biomechanics* 43: 343–8, 2010.

96. Kyritsis P, Bahr R, Landreau P, Miladi R, and Witvrouw E. Likelihood of ACL Graft Rupture: Not Meeting Six Clinical Discharge Criteria before Return to Sport Is Associated with a Four Times Greater Risk of Rupture. *British Journal of Sports Medicine* 50: 946–51, 2016.

97. Lloyd RS, Oliver JL, Kember LS, Myer GD, and Read PJ. Individual Hop Analysis and Reactive Strength Ratios Provide Better Discrimination of ACL Reconstructed Limb Deficits Than Triple Hop for Distance Scores in Athletes Returning to Sport. *Knee* 27: 1357–1364, 2020.

98. Lockie RG, Callaghan SJ, Berry SP, Cooke ER, Jordan CA, Luczo TM, and Jeffriess MD. Relationship between Unilateral Jumping Ability and Asymmetry on Multidirectional Speed in Team-Sport Athletes. *Journal of Strength and Conditioning Research* 28: 3557–66, 2014.

99. Losciale JM, Zdeb RM, Ledbetter L, Reiman MP, and Sell TC. The Association between Passing Return-to-Sport Criteria and Second Anterior Cruciate Ligament Injury Risk: A Systematic Review with Meta-Analysis. *Journal of Orthopaedic and Sports Physical Therapy* 49: 43–54, 2019.

100. Macdonald B, McAleer S, Kelly S, Chakraverty R, Johnston M, and Pollock N. Hamstring Rehabilitation in Elite Track and Field Athletes: Applying the British Athletics Muscle Injury Classification in Clinical Practice. *British Journal of Sports Medicine* 53: 1464–1473, 2019.

101. Mani K, Brechue WF, Friesenbichler B, and Maffiuletti NA. Validity and Reliability of a Novel Instrumented One-Legged Hop Test in Patients with Knee Injuries. *Knee* 24: 237–242, 2017.

102. Mauchly JW. Significance Test for Sphericity of a Normal *n*-Variate Distribution. *The Annals of Mathematical Statistics* 11: 204–209, 1940.

103. Maulder P and Cronin J. Horizontal and Vertical Jump Assessment: Reliability, Symmetry, Discriminative and Predictive Ability. *Physical Therapy in Sport* 6: 74–82, 2005.

104. Maulder PS, Bradshaw EJ, and Keogh J. Jump Kinetic Determinants of Sprint Acceleration Performance from Starting Blocks in Male Sprinters. *Journal of Sports Science and Medicine* 5: 359–66, 2006.

105. McFarlane B. Special Strength: Horizontal or Vertical. *Strength and Conditioning Journal* 6: 64–66, 1985.

106. McGuigan MRPCD, Cormack SJP, and Gill NDP. Strength and Power Profiling of Athletes: Selecting Tests and How to Use the Information for Program Design. *Strength and Conditioning Journal* 35: 7–14, 2013.

107. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, and Burke LM. Defining Training and Performance Caliber: A Participant Classification Framework. *International Journal of Sports Physiology and Performance* 17: 317–331, 2022.

108. McMaster DT, Gill N, Cronin J, and McGuigan M. A Brief Review of Strength and Ballistic Assessment Methodologies in Sport. *Sports Medicine* 44: 603–23, 2014.

109. Meylan C, McMaster T, Cronin J, Mohammad NI, Rogers C, and Deklerk M. Single-Leg Lateral, Horizontal, and Vertical Jump Assessment: Reliability, Interrelationships, and Ability to Predict Sprint and Change-of-Direction Performance. *Journal of Strength and Conditioning Research* 23: 1140–7, 2009.

110. Molla RY, Fatahi A, Khezri D, Ceylan HI, and Nobari H. Relationship between Impulse and Kinetic Variables during Jumping and Landing in Volleyball Players. *BMC Musculoskeletal Disorders* 24: 619, 2023.

111. Morin JB, Edouard P, and Samozino P. Technical Ability of Force Application as a Determinant Factor of Sprint Performance. *Medicine and Science in Sports and Exercise* 43: 1680–8, 2011.

112. Morin JB, Slawinski J, Dorel S, de Villareal ES, Couturier A, Samozino P, Brughelli M, and Rabita G. Acceleration Capability in Elite Sprinters and Ground Impulse: Push More, Brake Less? *Journal of Biomechanics* 48: 3149–54, 2015.

113. Müller U, Krüger-Franke M, Schmidt M, and Rosemeyer B. Predictive Parameters for Return to Pre-Injury Level of Sport 6 Months Following Anterior Cruciate Ligament Reconstruction Surgery. *Knee Surgery, Sports Traumatology, Arthroscopy* 23: 3623–3631, 2015.

114. Muniz TB, Moraes R, and Guirro RR. Lower Limb Ice Application Alters Ground Reaction Force during Gait Initiation. *Brazilian Journal of Physical Therapy* 19: 114–21, 2015.

115. Munro AG and Herrington LC. Between-Session Reliability of Four Hop Tests and the Agility T-Test. *Journal of Strength and Conditioning Research* 25: 1470–7, 2011.

116. Nagahara R and Gleadhill S. Asymmetries of Kinematics and Kinetics in Female and Male Sprinting. *Journal of Sports Medicine and Physical Fitness* 63: 891–898, 2023.

117. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Association of Sprint Performance with Ground Reaction Forces during Acceleration and Maximal Speed Phases in a Single Sprint. *Journal of Applied Biomechanics* 34: 104–110, 2018.

118. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Association of Step Width with Accelerated Sprinting Performance and Ground Reaction Force. *International Journal of Sports Medicine* 38: 534–540, 2017.

119. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Step-to-Step Spatiotemporal Variables and Ground Reaction Forces of Intra-Individual Fastest Sprinting in a Single Session. *Journal of Sports Sciences* 36: 1392–1401, 2018.

120. Nagahara R, Naito H, Morin JB, and Zushi K. Association of Acceleration with Spatiotemporal Variables in Maximal Sprinting. *International Journal of Sports Medicine* 35: 755–61, 2014.

121. Nesser TW, Latin RW, Berg K, and Prentice E. Physiological Determinants of 40-Meter Sprint Performance in Young Male Athletes. *Journal of Strength and Conditioning Research* 10: 263–267, 1996.

122. Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK, Robertson M, Pearson DR, Craig BW, Hakkinen K, and Kraemer WJ. Determination of Functional Strength Imbalance of the Lower Extremities. *Journal of Strength and Conditioning Research* 20: 971–7, 2006.

123. Norton KI. Standards for Anthropometry Assessment. *Kinanthropometry and Exercise Physiology: Volume One: Anthropometry*: 68, 2018.

124. Noyes FR, Barber SD, and Mangine RE. Abnormal Lower Limb Symmetry Determined by Function Hop Tests after Anterior Cruciate Ligament Rupture. *American Journal of Sports Medicine* 19: 513–8, 1991.

125. Pedley JS, Lloyd RS, Read PJ, Moore IS, Myer GD, and Oliver JL. A Novel Method to Categorize Stretch-Shortening Cycle Performance across Maturity in Youth Soccer Players. *The Journal of Strength and Conditioning Research* 36: 2573–2580, 2022.

126. Peterson RA. A Meta-Analysis of Cronbach's Coefficient Alpha. *Journal of Consumer Research* 21: 381–391, 1994.

127. Pueo B, Hopkins WG, Penichet-Tomas A, and Jimenez-Olmedo JM. Accuracy of Flight Time and Countermovement-Jump Height Estimated from Videos at Different Frame Rates with Myjump. *Biology of Sport* 40: 595–601, 2023.

128. Pueo B, Penichet-Tomas A, and Jimenez-Olmedo JM. Validity, Reliability and Usefulness of Smartphone and Kinovea Motion Analysis Software for Direct Measurement of Vertical Jump Height. *Physiology and Behavior* 227: 113144, 2020.

129. Rabita G, Dorel S, Slawinski J, Saez-de-Villarreal E, Couturier A, Samozino P, and Morin JB. Sprint Mechanics in World-Class Athletes: A New Insight into the Limits of Human Locomotion. *Scandinavian Journal of Medicine and Science in Sports* 25: 583–94, 2015.

130. Raoul T, Klouche S, Guerrier B, El-Hariri B, Herman S, Gerometta A, Lefevre N, and Bohu Y. Are Athletes Able to Resume Sport at Six-Month Mean Follow-up after Anterior Cruciate Ligament Reconstruction? Prospective Functional and Psychological Assessment from the French Anterior Cruciate Ligament Study (Fast) Cohort. *The Knee* 26: 155–164, 2019.

131. Reid A, Birmingham TB, Stratford PW, Alcock GK, and Giffin JR. Hop Testing Provides a Reliable and Valid Outcome Measure during Rehabilitation after Anterior Cruciate Ligament Reconstruction. *Physical Therapy* 87: 337–49, 2007.

132. Ross MD, Langford B, and Whelan PJ. Test-Retest Reliability of 4 Single-Leg Horizontal Hop Tests. *Journal of Strength and Conditioning Research* 16: 617–22, 2002.

133. Ruddock AD and Winter EM. Jumping Depends on Impulse Not Power. *Journal of Sports Sciences* 34: 584–5, 2016.

134. Sakadjian A, Panchuk D, and Pearce AJ. Kinematic and Kinetic Improvements Associated with Action Observation Facilitated Learning of the Power Clean in Australian Footballers. *Journal of Strength and Conditioning Research* 28: 1613–25, 2014.

135. Samozino P, Morin JB, Hintzy F, and Belli A. A Simple Method for Measuring Force, Velocity and Power Output during Squat Jump. *Journal of Biomechanics* 41: 2940–5, 2008.

136. Samozino P, Rabita G, Dorel S, Slawinski J, Peyrot N, Saez de Villarreal E, and Morin JB. A Simple Method for Measuring Power, Force, Velocity Properties, and Mechanical Effectiveness in Sprint Running. *Scandinavian Journal of Medicine and Science in Sports* 26: 648–58, 2016.

137. Sanudo B, Rueda D, Pozo-Cruz BD, de Hoyo M, and Carrasco L. Validation of a Video Analysis Software Package for Quantifying Movement Velocity in Resistance Exercises. *Journal of Strength and Conditioning Research* 30: 2934–41, 2016.

138. Šarabon N, Kozinc Z, and Bishop C. Comparison of Vertical and Horizontal Reactive Strength Index Variants and Association with Change of Direction Performance. *Journal of Strength and Conditioning Research* 37: 84–90, 2023.

139. Šarabon N, Milinović I, Dolenec A, Kozinc Ž, and Babić V. The Reactive Strength Index in Unilateral Hopping for Distance and Its Relationship to Sprinting Performance: How Many Hops Are Enough for a Comprehensive Evaluation? *Applied Sciences* 12: 11383, 2022.

140. Scataglini S, Abts E, Van Bocxlaer C, Van den Bussche M, Meletani S, and Truijen S. Accuracy, Validity, and Reliability of Markerless Camera-Based 3d Motion Capture Systems Versus Marker-Based 3d Motion Capture Systems in Gait Analysis: A Systematic Review and Meta-Analysis. *Sensors* 24: 3686, 2024.

141. Schuster D and Jones PA. Relationships between Unilateral Horizontal and Vertical Drop Jumps and 20 M Sprint Performance. *Physical Therapy in Sport* 21: 20–5, 2016.

142. Scott W, Adams C, Fisher J, Fisher S, Jones K, and Mathieu B. Electrically Elicited Quadriceps Muscle Torque: Comparison at Three Knee Angles. *Physiotherapy Theory and Practice* 37: 729–735, 2021.

143. Selistre LFA, Cintra GC, Junior A, Donizete R, and Rosa SMMG. Relationship between Extensor Torque and H: Q Ratio with Triple Hop Distance in Professional Soccer Players. *Revista Brasileira de Medicina do Esporte* 18: 390–393, 2012.

144. Shapiro SS and Wilk MB. An Analysis of Variance Test for Normality (Complete Samples). *Biometrika* 52: 591–611, 1965.

145. Shapiro SS, Wilk MB, and Chen HJ. A Comparative Study of Various Tests for Normality. *Journal of the American Statistical Association* 63: 1343–1372, 1968.

146. Sharp A, Neville J, Nagahara R, Wada T, and Cronin J. Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries during Multiple-Hops? *Biomechanics* 5: 67, 2025.

147. Sharp A, Neville J, Nagahara R, Wada T, and Cronin J. Using Multiple-Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen. *Applied Sciences* 15: 1685, 2025.

148. Sharp AP, Cronin JB, and Neville J. Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App. *Strength and Conditioning Journal* 41: 96–107, 2019.

149. Sharp AP, Cronin JB, Neville J, Diewald SN, Stolberg M, Draper N, and Walter S. Comparison of Multiple Hop Test Kinematics between Force-Platforms and Video Footage – a Cross Sectional Study. *International Journal of Kinesiology and Sports Science* 11: 23–28, 2023.

150. Sharp AP, Neville J, Diewald SN, Oranchuk DJ, and Cronin JB. Videographic Variability of Triple and Quintuple Horizontal Hop Performance. *Journal of Sport Rehabilitation* 33: 570–581, 2024.

151. Sharp AP, Neville J, Nagahara R, Wada T, and Cronin JB. Stretch-Load Demands in Multiple Hops: Implications for Athletic Performance and Rehabilitation. (in review), 2025.

152. Shrier I. Strategic Assessment of Risk and Risk Tolerance (STARRT) Framework for Return-to-Play Decision-Making. *British Journal of Sports Medicine* 49: 1311, 2015.

153. Sousa PL, Krych AJ, Cates RA, Levy BA, Stuart MJ, and Dahm DL. Return to Sport: Does Excellent 6-Month Strength and Function Following ACL Reconstruction Predict Midterm Outcomes? *Knee Surgery, Sports Traumatology, Arthroscopy* 25: 1356–1363, 2017.

154. Stanton R, Wintour SA, and Kean CO. Validity and Intra-Rater Reliability of Myjump App on iPhone 6s in Jump Performance. *Journal of Science and Medicine in Sport* 20: 518–523, 2017.

155. Stolberg M, Sharp AP, Comtois AS, Lloyd RS, Oliver JL, and Cronin J. Triple and Quintuple Hops: Utility, Reliability, Asymmetry, and Relationship to Performance. *Strength and Conditioning Journal* 38: 18–25, 2016.

156. Sugisaki N, Okada J, and Kanehisa H. Intensity-Level Assessment of Lower Body Plyometric Exercises Based on Mechanical Output of Lower Limb Joints. *Journal of Sports Sciences* 31: 894–906, 2013.

157. Templin T, Riehm CD, Eliason T, Hulburt TC, Kwak ST, Medjaouri O, Chambers D, Anand M, Saylor K, Myer GD, and Nicolella DP. Evaluation of Drop Vertical Jump Kinematics and Kinetics Using 3D Markerless Motion Capture in a Large Cohort. *Frontiers in Bioengineering and Biotechnology* 12: 1426677, 2024.

158. Van der Horst N, Backx F, Goedhart EA, Huisstede BM, and Group HI-D. Return to Play after Hamstring Injuries in Football (Soccer): A Worldwide Delphi Procedure Regarding Definition, Medical Criteria and Decision-Making. *British Journal of Sports Medicine* 51: 1583–1591, 2017.

159. Van Lieshout KG, Anderson JG, Shelburne KB, and Davidson BS. Intensity Rankings of Plyometric Exercises Using Joint Power Absorption. *Clinical Biomechanics* 29: 918–22, 2014.

160. Verrelst R, Van Tiggelen D, De Ridder R, and Witvrouw E. Kinematic Chain-Related Risk Factors in the Development of Lower Extremity Injuries in Women: A Prospective Study. *Scandinavian Journal of Medicine and Science in Sports* 28: 696–703, 2018.

161. Vittori C. The European School in Sprint Training: The Experiences in Italy. *New Studies in Athletics* 11: 85–92, 1996.

162. Vittori C. Monitoring the Training of the Sprinter. *New Studies in Athletics* 10: 39–44, 1995.

163. Webster KE and Feller JA. Clinical Tests Can Be Used to Screen for Second Anterior Cruciate Ligament Injury in Younger Patients Who Return to Sport. *Orthopaedic Journal of Sports Medicine* 7: 2325967119863003, 2019.

164. Weir JP. Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. *Journal of Strength and Conditioning Research* 19: 231–40, 2005.

165. Wellsandt E, Failla MJ, and Snyder-Mackler L. Limb Symmetry Indexes Can Overestimate Knee Function after Anterior Cruciate Ligament Injury. *Journal of Orthopaedic and Sports Physical Therapy* 47: 334–338, 2017.

166. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The Biological Limits to Running Speed Are Imposed from the Ground Up. *Journal of Applied Physiology* 108: 950–61, 2010.

167. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster Top Running Speeds Are Achieved with Greater Ground Forces Not More Rapid Leg Movements. *Journal of Applied Physiology* 89: 1991–9, 2000.

168. White MS, Horton WZ, Burland JP, Seeley MK, and Lepley LK. The Utility of Functional Data Analyses to Reveal between-Limbs Asymmetries in Those with a History of Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training* 56: 272–279, 2021.

169. Xergia SA, Pappas E, Zampeli F, Georgiou S, and Georgoulis AD. Asymmetries in Functional Hop Tests, Lower Extremity Kinematics, and Isokinetic Strength Persist 6 to 9 Months Following Anterior Cruciate Ligament Reconstruction. *Journal of Orthopaedic and Sports Physical Therapy* 43: 154–62, 2013.

170. Young W, McLean B, and Ardagna J. Relationship between Strength Qualities and Sprinting Performance. *Journal of Sports Medicine and Physical Fitness* 35: 13–9, 1995.

171. Young WB, James R, and Montgomery I. Is Muscle Power Related to Running Speed with Changes of Direction? *Journal of Sports Medicine and Physical Fitness* 42: 282–8, 2002.

172. Zarro M, Dickman M, Hulett T, Rowland R, Larkins D, Taylor J, and Nelson C. Hop to It! The Relationship between Hop Tests and the Anterior Cruciate Ligament: Return to Sport Index after Anterior Cruciate Ligament Reconstruction in NCAA Division 1 Collegiate Athletes. *International Journal of Sports Physical Therapy* 18: 1076–1084, 2023.

173. Zhou W, Liu X, Hong Q, Wang J, and Luo X. Association between Passing Return-to-Sport Testing and Re-Injury Risk in Patients after Anterior Cruciate Ligament Reconstruction Surgery: A Systematic Review and Meta-Analysis. *PeerJ* 12: e17279, 2024.

# APPENDICES

# Appendix I: Ethics Approval (AUTEC)

**AUTEC Secretariat**

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

24 July 2017

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **17/133 Multiple hop testing - the diagnostic value to athlete profiling**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 24 July 2020.

**Standard Conditions of Approval**

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

**Non-Standard Conditions of Approval**

1. Complete contact details for the Research Assistant in the Information Sheet;
2. Complete the withdrawal statement in relation to withdrawal of data.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

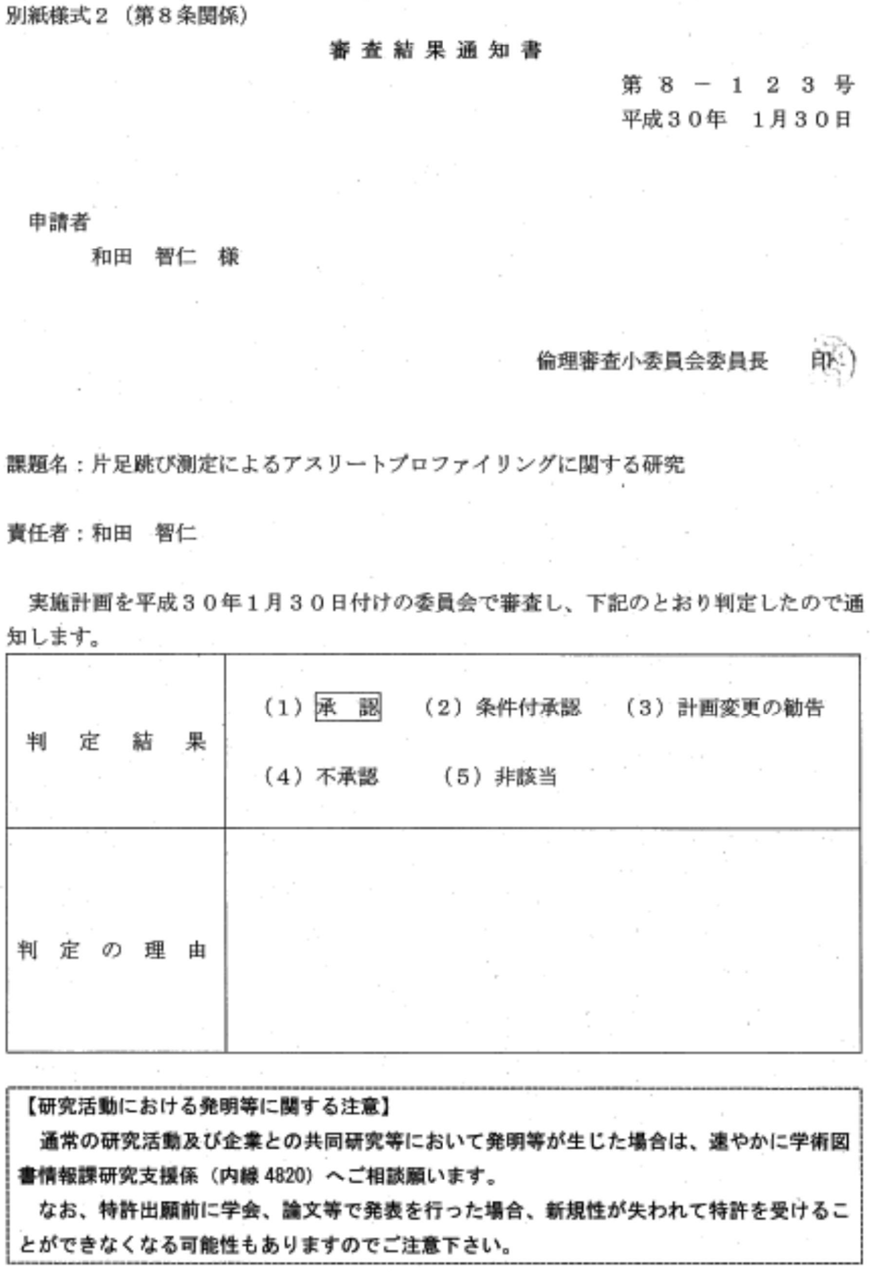
For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
**Auckland University of Technology Ethics Committee**

Cc: asharp@nzcricket.org.nz; jono@qsportstechnology.com

# Appendix II: Ethics Approval (NIFS)



別紙様式２（第８条関係）

審査結果通知書

第８－１２３号
平成３０年　１月３０日

申請者
和田　智仁　様

倫理審査小委員会委員長　印

課題名：片足跳び測定によるアスリートプロファイリングに関する研究

責任者：和田　智仁

実施計画を平成３０年１月３０日付けの委員会で審査し、下記のとおり判定したので通知します。

| | |
|---|---|
| 判定結果 | （１）[✓ 承認]　（２）条件付承認　（３）計画変更の勧告<br>（４）不承認　（５）非該当 |
| 判定の理由 | |

【研究活動における発明等に関する注意】

通常の研究活動及び企業との共同研究等において発明等が生じた場合は、速やかに学術図書情報課研究支援係（内線 4820）へご相談願います。

なお、特許出願前に学会、論文等で発表を行った場合、新規性が失われて特許を受けることができなくなる可能性もありますのでご注意下さい。

# Appendix III: Triple and Quintuple Hops: Utility, Reliability Asymmetry and Relationship to Performance.

# Triple and Quintuple Hops: Utility, Reliability, Asymmetry, and Relationship to Performance

Michael Stolberg, MSc,[1,2,3] Anthony Sharp, MSc,[3,4] Alain S. Comtois, PhD,[1] Rhodri S. Lloyd, PhD,[5] Jon L. Oliver, PhD,[5] and John Cronin, PhD[3,6]
[1]Department of Physical Activity Sciences, Université du Québec à Montréal (UQAM), Montreal, Québec, Canada; [2]Institut National du Sport du Québec (INS Québec), Montreal, Québec, Canada; [3]Sport Performance Research Institute New Zealand, AUT Millennium Instutute, AUT University, Auckland, New Zealand; [4]New Zealand Cricket, Lincoln, New Zealand; [5]Youth Physical Development Unit, School of Sport, Cardiff Metropolitan University, Cardiff, United Kingdom; and [6]School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, Australia

## ABSTRACT

TRIPLE AND QUINTUPLE HOPS (THT AND QHT, RESPECTIVELY) ARE USED TO TEST REPEATED PROPULSION. THIS NARRATIVE REVIEW PROVIDES INFORMATION REGARDING THE USE OF THT AND QHT, AS WELL AS THEIR RELIABILITY, TESTING NORMS BY SEX AND ATHLETIC LEVEL, THEIR ABILITY IN DETECTING ASYMMETRY AND RELEVANCE TO OTHER PERFORMANCE MEASURES. THE TESTS' RELIABILITY (INTRACLASS CORRELATION COEFFICIENT [ICC]$_{THT}$ = 0.80–0.98; STANDARD ERROR OF THE MEAN [SEM]$_{THT}$ = 0.11–0.23 M; ICC$_{QHT}$ = 0.89) WARRANTS THEIR INCLUSION DURING TESTING BATTERIES. THT RANGES FROM 4.28 TO 6.90 M AND ASYMMETRIES RANGE FROM 10 TO 15%. THT IS LIKELY RELATED TO ACCELERATION CAPABILITIES. PRACTICAL RECOMMENDATIONS ARE PROVIDED TO PRACTITIONERS REGARDING TESTS' ADMINISTRATION.

Address correspondence to Michael Stolberg, stolberg.m@gmail.com.

**KEY DEFINITIONS**

Hop: the propulsion and landing of one's body on a single leg, once or multiple times; finally landing on one or 2 legs.

Triple hops: a test requiring the participant to stand on one leg and to hop forward 3 times, landing from the third hop on 2 legs.

Quintuple hops: a test requiring the participant to stand on one leg and to hop forward 5 times, landing from the fifth hop on 2 legs.

Hop distance differences between limbs are described in various ways in the literature. Though this review will use the term asymmetry, terms such as interlimb imbalance and symmetry index are common. The former describes how much difference there is between the 2 limbs, whereas the latter represents how similar the 2 limbs are to each other.

Interlimb imbalance: (strong leg − weak leg)/strong leg × 100.

Symmetry index: (nondominant leg/dominant leg) × 100.

## INTRODUCTION

Ballistic movements such as jumps, sprints, and throws are an integral part of many sports and as such, athletic success relies on their proficiency (2). A recent review of ballistic movement assessments (13) reported that most lower body protocols involve some form of bilateral vertical jumping. Though this seems to be common practice in the literature, very few athletic activities require the participant to propel oneself solely vertically and in a bilateral fashion. Rather, most sports demand multiplanar propulsion, that is, an athlete may need to execute a powerful action, involving vertical, horizontal, and lateral

**KEY WORDS:**
field test; horizontal propulsion; jump; sprinting; unilateral

components simultaneously, for example diagonal change of direction in response to an opponent's motion. Furthermore, the majority of sporting motions require the body to move in an asymmetrical fashion, where the left and right sides of the body perform different tasks such as pitching in baseball or punting in rugby. Finally, most sport specific situations require propulsion that is cyclic rather than singular that is acyclic. Therefore, a thorough understanding of cyclic, unilateral, multi-axial propulsion would seem to be of importance for optimal athletic performance requiring such modes of acceleration.

The scientific literature contains a multitude of studies on unilateral horizontal propulsion assessments. These include tests such as: single hop for distance (1,8,16,20,22), triple hop for distance (1,8,16,20,22), 6-m hop for time (16,20), crossover hop for distance (16,20,22), and more recently, lateral countermovement jump (14). It should be noted that in many cases these hops are used in a clinical setting, especially with regards to knee injuries and their rehabilitation. Hopping ability, as it relates to performance in a healthy athlete population is seldom addressed in the literature. Though single and triple hop for distance, both seem to be administered within testing batteries for athletic populations, the former test lacks cyclic unilateral impact absorption and subsequent propulsion, which is fundamental to the triple hop. This component would seem to be of high importance in sports that require the athlete to propel oneself cyclically.

Another similar test that is used in training and assessment regimens is the quintuple hop for distance, referred to as the 5-hop test in the literature (18). Like its triple hop counterpart, this test requires cyclical impact absorption followed by propulsion, over a longer distance. Although the quintuple hop for distance is a test with minimal research, its use by practitioners warrants its inclusion in this review.

The purpose of this review is to provide an understanding of the triple and quintuple hops, specifically the reliability and testing norms will be reviewed. This will be followed by a discussion on aspects of asymmetry and relationship of testing results to other performance indicators. Finally, a discussion of limitations as pertaining to the testing protocols, evidence-based recommendations will be provided so that the practitioner may administer these tests in an appropriate fashion.

## SEARCH STRATEGY

To obtain articles for the review, a search of internet databases Scopus, PubMed, Google Scholar and Web of Science, was conducted. The following keywords were used: "triple hop," "quintuple hop," "horizontal jump," and "hop test." The bibliographies of all reviewed articles were then searched and also reviewed. Studies were chosen for inclusion if they fulfilled one of the following 3 selection criteria: (a) the study investigated the reliability of the triple and/or the quintuple hop; (b) the study investigated limb asymmetry during triple and/or the quintuple hop; and (c) the study reported relationships between hopping distance on the triple and/or the quintuple hop and other performance parameters (e.g., 10 m sprint time). All studies included had to satisfy the following 4 criteria: (a) the study gave detailed information about male and/or female participants' characteristics (i.e., age above 18 years, training status, and main activity); (b) the study presented group means and standard deviations for the dependent variable (hop distance); (c) study participants were healthy and had not reported major musculoskeletal injuries to the lower limb; and (d) studies had to be written in the English language and must have been published as a full text article in a peer-reviewed journal.

## DATA COLLECTION AND SYNTHESIS

Nine studies satisfied the inclusion criteria. The following characteristics were recorded for all articles: authors and year of publication. To adequately compare studies, the following study parameters were noted and categorized according to: demographics (sample size, age, sex and training status); testing variation (type of hop, number of testing trials, number of testing sessions and leg on which hops were performed); absolute and relative reliability (intraclass correlation coefficient [ICC], standard error of the mean [SEM], coefficient of variation [CV], standard error of the estimate, smallest detectable difference, and 95% confidence interval [95% CI] values); testing performance (hopping distance and interlimb asymmetry of hop distance); and performance validity (relationship between hopping distance and other tests). It should be noted that out of all the studies satisfying the inclusion criteria, only one study (18) investigated the quintuple hop for distance, with all others solely focusing on the triple hop.

## RELIABILITY

The reliability of triple hop protocols has been reported in 5 studies (3,6,12,16,20) (Table 1) and the quintuple hop having been studied once (18). In regard to the triple hop research, most ICCs were greater than 0.90 with the exception of one study (16) which reported an ICC of 0.80 for their female university students, which was less than the ICCs reported for their male counterparts (0.92). Overall, the reliability of the triple hop seems to be excellent with an ICC value $\geq$0.80 in all studies. It must be noted that when interpreting the ICC, which serves as an index of relative or rank order reliability, it should be interpreted cautiously when both male and female data are pooled. For example, some authors (3,6) have aggregated both female and male data, which most likely artificially inflated the ICC due to the greater heterogeneity of the group and thus may have overestimated the reliability of the hopping protocol. ICC values between 0.95 and 0.98 (3,6) were reported in these instances.

In terms of the measures of typical error (CV and SEM) for the triple hops, it seems that CVs of less than 2% and SEMs of 11–17 cm are common. One study (16) reported greater variability for their female participants–SEM = 23.18 cm. This was the only study to compare males and females independently,

**Table 1**
**Triple hop tests reliability**

| Authors | Participants | Reliability protocol | Mean ± standard deviation (m) | Standard error of the mean (m) | Coefficient of variation (%) | Smallest detectable difference (m) | 95% confidence interval (m) | Intraclass correlation coefficient |
|---|---|---|---|---|---|---|---|---|
| Bolgla and Keskula (3) | 15 females, 5 males; 24.5 ± 4.2 y old | Test, retest (48 h interval) | N/A | 0.15 | N/A | N/A | N/A | 0.95 |
| Hamilton et al. (6) | 20 females, 20 males; 18–23 y old | N/A | N/A | 0.16 | N/A | N/A | N/A | 0.98 |
| Maulder and Cronin (12) | 18 males; 25.1 ± 4.3 y old | Test, retest reliability (2–7 d interval) | Dominant leg: 5.14 ± 0.794; Nondominant leg: 5.27 ± 0.64 | N/A | Dominant leg: 1.9; Nondominant leg: 1.8 | N/A | N/A | Dominant leg: 0.97; Nondominant leg: 0.95 |
| Munro and Herrington (16) | 11 females; 22.3 ± 3.7 y old; 11 males; 22.8 ± 3.1 y old | Test, retest (3 sessions with 1 wk intervals) | N/A | Females: 0.23; Males: 0.17 | N/A | Females: 0.64; Males: 0.48 | Females: 4.98–5.12; Males: 5.76–5.93 | Females: 0.80; Males: 0.92 |
| Ross et al. (20) | 18 males; 20.2 ± 1.2 y old | Test, retest (4 wk interval) | N/A | 0.11 | N/A | N/A | N/A | 0.97 |

T1: test 1; T2: test 2.

therefore, more research is needed to determine whether or not movement variability is greater with females or the results are specific to this sample. It is interesting to note that similarly, an increase in variability was noted in women compared with men in vertical jumping (4).

The only researchers (18) to have quantified quintuple hop reliability, reported an ICC of 0.89 for female college softball players. It seems that the quintuple hop test is reliable, however, it is recommended that further research into its reliability be undertaken for females and males separately, as well as within well-defined populations, that is, recreational versus elite athletes. Furthermore, measures of typical error (CV, SEM) associated with the quintuple hop are needed to truly appreciate the reliability of this protocol.

## NORMATIVE DATA

When examining the published hop test results, a large range of hopping distances can be observed (Table 2). In terms of triple hop, mean results range from 4.28 ± 0.64 m (3) to 6.90 ± 0.40 m (11). Male data ranged from 5.105 ± 0.740 m to 6.90 ± 0.21 m. Due to a lack of data within the literature, no range for female results can be produced. Only one study (16) made comparisons between sexes, or produced female-only data for that matter. They reported mean distances of 5.05 ± 0.52 and 5.85 ± 0.61 m for females and males, respectively. Male hopping distances were 13.6% greater than those of females, within a recreationally active young adult population. Highly trained individuals and amateur and professional athletes achieve greater distance on the triple hop test compared with recreationally active counterparts (5,11,12,20,21).

Within protocols that restricted upper limb movement but allowed landing on both legs, mean hopping distances ranged from 5.11 ± 0.74 to 6.90 ± 0.21 m (11,12). Participants in these studies ranged from physically active males to national level sprinters. On the other hand, researchers who allowed upper limb use but demanded final landings on the hopping leg only reported means

Table 2

Triple hop test normative data

| Authors | Subjects, gender, age, sport | Technique | Triple hop test distance mean ± standard deviation (m) |
|---|---|---|---|
| Bolgla and Keskula (3) | 15 females, 5 males; 24.5 ± 4.2 y old | Triple hop test (dominant limb—kicking limb) | T1: 4.28 ± 0.64, T2: 4.31 ± 0.76 |
| Habibi et al. (5) | 15 males; 21.89 ± 3.26 y old regional and national level track sprinters. Mean 100 m time of 11.67 ± 0.46 (11.00–12.19 s) | Triple hop test (left and right), Land on 2 feet, Arms on hips | Block front leg: 6.63 ± 0.57, Block back leg: 6.50 ± 0.57 |
| Hamilton et al. (6) | 20 females, 20 males; 18–23 y old, NCAA DI-AA Soccer | Triple hop test (dominant limb—stance limb during kick), Arm swing | 5.47 ± 0.97, Max: 7.81, Min: 3.83 |
| Maulder and Cronin (12) | 18 males; 25.1 ± 4.3 y old, Physically active in sports predominantly involving lower limbs | Triple hop test (left and right), Land on 2 feet, Arms on hips | Dominant leg: 5.11 ± 0.74, Nondominant leg: 5.12 ± 0.66 |
| Maulder et al. (11) | 10 males; 20 ± 3 y old, Regional and national level track sprinters. Mean 100 m time of 10.87 ± 0.36 (10.37–11.42 s) | Triple hop test (left and right), Land on 2 feet, Arms on hips | Block front leg: 6.90 ± 0.21, Max: 7.30, Min: 6.68, Block back leg: 6.90 ± 0.40, Max: 7.53, Min: 6.31 |
| Munro and Herrington (16) | 11 females; 22.3 ± 3.7 y old, 11 males; 22.8 ± 3.1 y old, University students, Min: 30 min PA 3/wk | Triple hop test (left and right), Dominant limb—kicking limb, Maintain balance on landing (2 s), Arm swing | Females: 5.05 ± 0.52, Males: 5.85 ± 0.61 |
| Ross et al. (20) | 18 males; 20.2 ± 1.2 y old, US Air Force Academy cadets | Triple hop test (1 leg determined at random), No restriction of upper limbs | T1: 6.70 ± 0.64, T2: 6.73 ± 0.66 |
| Selistre et al. (21) | 21 males; 23.2 ± 3.6 y old, Second league Sao Paulo State Championship, Professional Soccer | Triple hop test (left and right), Arm swing, Land 1 foot, other foot can't touch ground | Dominant leg: 6.65, Nondominant leg: 6.74 |

T1: test 1; T2: test 2.

ranging from 5.85 ± 0.61 to 6.74 m (16,21). Participants in these studies ranged from active male university students to professional soccer players.

Though interstudy differences are difficult to interpret, it is possible that arm swing enables greater triple hop distances to be achieved, at least in recreationally active males. However, in terms of highly trained participants it seems that the top performing sprinters of the Maulder et al. (11) study would have hopped even greater distances using arm swing, because they had the greatest mean distance in the literature reviewed and were restricted in terms of upper limb movement.

The one study which examined the quintuple hop distances reported mean values of 7.71 ± 1.06 and 7.81 ± 1.14 m for the right and left legs, respectively. The researchers also reported mean values of hop distances with respect to personal leg preference as 7.92 ± 1.08 and 7.59 ± 1.10 m for the dominant and nondominant legs, respectively (18).

Overall normative data exists for certain populations, namely recreationally active men and women as well as elite level male athletes for the triple hops. Additionally, quintuple hops' normative data exist for female athletes (18). Future research needs to focus on triple hop norms for female athletes and collecting further normative data for the quintuple hop across all populations. Furthermore, it is advised that interpopulation data pooling (whether female and male or recreational and elite) be avoided so that gender-specific and athletic level-specific norms can be established. Finally, protocol uniformity is advised to help the practitioner compare normative data across populations.

## ASYMMETRY

Triple hop limb asymmetry was examined in recreationally active adults. Mean symmetry index scores between 99.32 ± 5.82% and 101 ± 5% were reported for males, whereas females were reported to have mean scores of 98.87 ± 6.87% (15,19). It should be noted that a symmetry index score below 100% signifies that the dominant leg (preferred kicking leg in the case of these studies) covered a greater distance, whereas a score above 100% describes that the nondominant leg covered a greater distance. When male and female data are pooled less asymmetry is evident (i.e., symmetry of at least 90%), however, male only symmetry index data seem to be greater than 85%. These studies are thus in agreement with previous research using other movement patterns that cite limb asymmetry is approximately 10–15% in healthy, recreationally active adults (15).

The one study that examined quintuple hops assessed its effect on interlimb asymmetry (18). The researchers reported a symmetry of 99.08 ± 5.34% ($p > 0.05$) between left and right legs. When legs were designated as dominant and nondominant, the symmetry was of 95.76 ± 2.61% ($p < 0.05$), thus demonstrating the possible utility in reporting interlimb differences in terms of leg dominance for more appropriate comparisons between subjects and groups. Considering that the triple hop studies reported symmetry index means of close to 99%, whereas this study reported a mean symmetry of approximately 96%, it could suggest that limb asymmetry is magnified when using the quintuple hop compared with the triple hop. This intuitively makes sense in that any asymmetry would be magnified with greater number of hops, however, triple and quintuple asymmetry needs to be assessed in the same populations to validate such a contention.

It should be noted that a recent review on asymmetries in hops raised the issue of reporting mean values for asymmetries (7). The review points to the fact that reporting asymmetry data as means and standard deviations masks the individual asymmetries of participants. Thus, the presentation of the data in this fashion is not as beneficial to the practitioner when trying to understand the extent to which limb asymmetry affects the individual athlete.

## RELATIONSHIP TO PERFORMANCE

Due to the similarity in vector of force application between hop tests and sprints, some researchers have investigated the relationships between the 2 modes of propulsion. Three studies (5,11,12) examined the relationship between triple hop distance and short (10–20 m) sprint performances, with some variability observed between these studies (r = 0.24–0.89). A very large correlation (r = −0.86) between jump distance and 20 m sprint time was reported in recreational male athletes (12). Similar correlations (r = −0.84 to −0.89) were observed for trained sprinters (5). However, in another study using highly trained sprinters much lower correlations (r = −0.24) were observed between jump distance and 10 m block start sprint times (11). It is difficult to explain the disparity between the results of the latter 2 studies, however, the smaller sample size ($n = 10$) and homogeneity of the sample used by Maulder and Cronin (12) might have influenced the magnitude of the correlation. Further research is needed to determine the relationship between the triple hop and sprint performance, and it would be interesting to quantify the triple hop test by other means than simply distance hopped.

The same researchers have also investigated the relationship between short sprints and jumping ability. For recreationally active males, countermovement jump (CMJ) height was found to be significantly related to 20 m sprint times (r = −0.73) (12). Among highly trained sprinters (5), though, no significant correlations were reported between sprint times and CMJ height. Maulder et al. (11) reported that highly trained sprinters' average and peak power output during the take-off phase of CMJ were significantly related to sprint times (r = −0.79 and r = 0.77, respectively), however, jump height from a CMJ was not (r = −0.13). The somewhat mixed findings may indicate that CMJ jump height is not the most appropriate measure to relate to performance and that the triple hop tests may be better predictors of sprint performance given the magnitude of the relationships. Intuitively, this would make sense given the unilateral and cyclic co-ordination patterns involved in the horizontal hopping task. In addition, a 5-step jump test was reported to have very large correlation with 40 m sprint time, whereas the vertical jump only had moderate correlations (r = −0.810; r = −0.464, respectively) (17). This further lends evidence to the fact that forward propulsion tests are more related to sprinting ability than vertical jumping.

The relationships between hop distance and CMJ height have also been investigated. Of interest is the degree of shared variance and if either provides differential diagnostic information. Among recreational male athletes and mixed sex active adults, very large correlations were reported (r = 0.83–0.86) as pertaining to the triple hop (8,15). The only researchers (18) to examine quintuple hop distances and their relation to CMJ, did not report jump height. The study did report though that quintuple hop distances were correlated with both CMJ peak and average force (r = 0.63, r = 0.53, respectively). Future research should investigate whether the reported shared variance between triple hop distance and CMJ height depends on sex and athletic level. Furthermore, the relation between quintuple hop distance and CMJ height needs to be investigated and looked at in relation to triple hops.

Finally, researchers investigated the relations between hop tests and muscle torques at different velocities. Very large correlations between triple hop distances and quadriceps and hamstring torques at 60 and 180°/s (r = 0.70–0.77) have been reported (6). However, because the results of both female and males were combined, these correlations may be artificially inflated. Researchers investigating males only (21) reported much lower values at muscle torques of 60, 180 and 300°/s (r = 0.01–0.48). Similarly, correlations of −0.147 with 0.573 have been reported between the quintuple hop and muscle torques at 60 and 240°/s for female athletes (18). Research findings in this area seem to be mixed in regard to the relationship between field tests and isokinetic muscular strength assessments. It is quite likely that single joint isokinetic motion has very different demands to ballistic multi-joint movement, which may in part explain the mixed research findings.

## PRACTICAL CONSIDERATIONS

Practitioners must be cognizant of a few testing variables so as to choose the most appropriate protocol in the context of their athlete evaluation.

### *HOPPING TECHNIQUE*

Test administrators are presented with differing hopping protocols in the literature, which cannot be directly compared. For example, 3 studies (5,11,12) prevented participants from aiding their hopping with their arms by placing the hands on the hips during the trials. Conversely, several researchers allowed and/or encouraged arm swing during the hops (6,16,20,21). The effect of using an arm swing has been documented in regard to vertical jumping (9,10). It was shown that such a strategy increased both the height and velocity of the jumper's center of mass at takeoff and led to a higher jump height (+19%) (9). This advantage is conferred to a greater degree during maximum effort jumps. It would be expected that arm swing would also allow participants to hop a greater distance, therefore making comparisons between data collected with and without arm swing difficult. Nevertheless, hopping with the contribution of the upper limbs is a more functional movement pattern (face and logical validity) and it would be reasonable to think that such a movement pattern may better transfer to other athletic activities in which lower and upper limbs move in synergy with each other (e.g., sprinting).

Another factor to consider is the landing from the last hop. A variety of landing instructions may be found in the literature, ranging from 2 feet (5,11,12,18), to one foot (6,20,21), to maintaining balance on one foot (16). Whether an athlete has to land on one or 2 feet and whether balance has to be maintained on landing may change the distance one can hop. This could have to do with the fact that on landing, a wider base of support offered by 2 feet will increase the likelihood of the participant maintaining their position without falling, which otherwise would render the hop invalid. Furthermore, it was shown that unilateral landing, during a vertical jump, increased knee valgus and demonstrated other differences in knee kinematics as well as EMG of muscles crossing the knee joint as compared with bilateral landing (19). These differences were accentuated among female participants. Thus a unilateral landing may force participants to curb their hopping performance to limit ground contact forces, which may cause injury on landing. Thus these variations in technique make for poor comparisons between differently administered testing protocols.

### *NOMENCLATURE*

The literature contains a variety of nomenclatures relating to the hopping leg. Studies looking at sprinters (5,11) used a clear descriptive nomenclature with the terms front and back block legs. However, other authors used the terminology of dominant and non-dominant legs. The leg used for kicking was assumed to be the dominant leg in some protocols (3,12,16,21), whereas one study (6) chose to call the stance leg during a kick the dominant leg. Thus practitioners must be clear on their own terminology so as to be able to make appropriate comparisons with testing norms found in the literature.

## PRACTICAL APPLICATIONS

As a result of the above raised issues it is advised that a consensus be reached on the protocol to be used for the triple and quintuple hops so as to create a uniformity in hopping technique. This would enable the establishment of valid norms for specific populations and that appropriate cross-study comparisons can be carried out.

Taking the above-mentioned considerations into account, the authors suggest the following guidelines for future triple and quintuple hop protocols in healthy populations.

- No arm swing (hand on hips) if the propulsive ability of the legs needs to be determined, however, if relating to functional performance then permit arm swing
- Bilateral support on final landing if testing in relation to maximum effort performance, prioritize unilateral landing if single leg static stability is deemed important
- Nominate the preferred hopping leg as the dominant one

Improved standardization of the triple and quintuple hops may help increase their specificity and potential utility for strength and conditioning coaches, though prospective studies of athletes monitored with hop tests are needed to confirm the hypothesized utility of these tests. The triple hop test has been found to be a reliable assessment, whereas the quintuple hop assessment needs further research to determine its validity, reliability, and sensitivity. Triple hop distance seems to be related to sprinting and vertical jump performance, whereas the relation of quintuple hops to other performance parameters needs additional research. Both tests would benefit from metrics other than hop distance, to better understand their relationship to other performance markers and possibly enhance their diagnostic value.

## CONCLUSION

Triple and quintuple hops seem to be of diagnostic value when assessing cyclic horizontal propulsion. Hop distance likely depends on the hopping protocol used (propulsion and landing mechanics) and thus great care must be taken when comparing the results obtained with normative data contained in the literature. Consequently, a standardized triple and quintuple hop protocol would be of great benefit to researchers and practitioners alike.

Triple hop tests have been found to have excellent reliability among uninjured adults, with females potentially showing greater movement variability. Female only data on the triple hop is scarce, thus future research focusing on this population is warranted. Additionally, the quintuple hop is a test that for all intents and purposes has undergone little scrutiny and therefore would benefit from a great deal of research focus, for example determining validity, reliability, and sensitivity.

It seems that healthy active individuals display a leg asymmetry of 10–15% when triple hops are used. Quintuple hops may increase the degree of interlimb asymmetry, though this remains to be verified. Of importance for future research is to describe asymmetries in a more informative manner than only mean scores, such that one may understand to which degree limb asymmetry affects athletes on an individual level.

Though triple hop distance seems to be a good indicator of performance in tasks requiring repeated propulsion, the literature contains mixed data on the matter and further research is needed before a definitive stance can be taken with regards to the test. Quantification of the triple hop test by means of other than simply through distance measures may improve the utility of the test. The quintuple hop test is not well researched and it is recommended that it be evaluated against other ballistic tests such as sprints and jumps to determine the diagnostic value of this assessment.

*Conflicts of Interest and Source of Funding: The authors report no conflicts of interest and no source of funding.*

**Michael Stolberg** *is a strength and conditioning coach, INS Québec and professional member of the Human Performance Laboratory, UQAM.*

**Anthony Sharp** *is a doctoral student, Sport Performance Research Institute New Zealand (SPRINZ), and a high performance strength and conditioning manager, New Zealand Cricket.*

**Alain S. Comtois** *is the director of graduate studies and professor in the department of Physical Activity Sciences, UQAM.*

**Rhodri S. Lloyd** *is a lecturer in sport and exercise physiology, Cardiff Metropolitan University.*

**Jon L. Oliver** *is a senior lecturer in sport and exercise physiology, Cardiff Metropolitan University in Cardiff.*

**John Cronin** *is the co-director and professor of strength and conditioning, Sport Performance Research Institute New Zealand (SPRINZ) and an adjunct professor, Edith Cowan University.*

## REFERENCES

1. Andrade MS, Cohen M, Piçarro IC, and Silva AC. Knee performance after anterior cruciate ligament reconstruction. *Isokinet Exerc Sci* 10: 81–86, 2002.
2. Baker DG and Newton RU. Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *J Strength Cond Res* 22: 153–158, 2008.
3. Bolgla LA and Keskula DR. Reliability of lower extremity functional performance tests. *J Orthop Sports Phys Ther* 26: 138–142, 1997.
4. Ditroilo M, Forte R, Mckeown D, Boreham C, and De Vito G. Intra- and intersession reliability of vertical jump performance in healthy middle-aged and older men and women. *J Sports Sci* 29: 1675–1682, 2011.
5. Habibi A, Shabani M, Rahimi E, Fatemi R, Najafi A, Analoei H, and Hosseini M. Relationship between jump test results and acceleration phase of sprint performance in national and regional 100m sprinters. *J Hum Kinet* 23: 29–35, 2010.
6. Hamilton RT, Shultz SJ, Schmitz RJ, and Perrin DH. Triple-hop distance as a valid predictor of lower limb strength and power. *J Athl Train* 43: 144, 2008.
7. Hewit J, Cronin J, and Hume P. Multidirectional leg asymmetry assessment in sport. *Strength Cond J* 34: 82–86, 2012.
8. Keays SL, Bullock-Saxton JE, Keays AC, Newcombe PA, and Bullock MI. A 6-year follow-up of the effect of graft site on strength, stability, range of motion, function, and joint degeneration after anterior cruciate ligament reconstruction: Patellar tendon versus semitendinosus and gracilis tendon graft. *Am J Sports Med* 35: 729–739, 2007.
9. Lees A, Vanrenterghem J, and De Clercq D. Understanding how an arm swing enhances performance in the vertical jump. *J Biomech* 37: 1929–1940, 2004.
10. Lees A, Vanrenterghem J, and De Clercq D. The energetics and benefit of an arm swing in submaximal and maximal vertical jump performance. *J Sports Sci* 24: 51–57, 2006.
11. Maulder P, Bradshaw E, and Keogh J. Jump kinetic determinants of sprint acceleration performance from starting blocks in male sprinters. *J Sport Sci Med* 5: 359–366, 2006.
12. Maulder P and Cronin J. Horizontal and vertical jump assessment: Reliability, symmetry, discriminative, and predictive ability. *Phys Ther Sport* 6: 74–82, 2005.
13. McMaster DT, Gill N, Cronin J, and McGuigan M. A brief review of strength and ballistic assessment methodologies in sport. *Sport Med* 44: 603–623, 2014.
14. Meylan C, McMaster T, Cronin J, Mohammad NI, Rogers C, and DeKlerk M. Single-leg lateral, horizontal, and vertical jump assessment: Reliability, interrelationships, and ability to predict sprint and change-of-direction

performance. *J Strength Cond Res* 23: 1140–1147, 2009.

15. Müller U, Krüger-Franke M, Schmidt M, and Rosemeyer B. Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. *Knee Surg Sports Traumatol Arthrosc* 23: 3623–3631, 2014.
16. Munro AG and Herrington LC. Between-session reliability of four hop tests and the agility T-test. *J Strength Cond Res* 25: 1470–1477, 2011.
17. Nesser TW, Latin RW, Berg K, and Prentice E. Physiological determinants of 40-meter sprint performance in young male athletes. *J Strength Cond Res* 10: 263–267, 1996.
18. Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK, Robertson M, Pearson DR, Craig BW, Häkkinen K, and Kraemer WJ. Determination of functional strength imbalance of the lower extremities. *J Strength Cond Res* 20: 971–977, 2006.
19. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, and Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clin J Sport Med* 17: 263–268, 2007.
20. Ross MD, Langford B, and Whelan PJ. Test–retest reliability of 4 single-leg horizontal hop tests. *J Strength Cond Res* 16: 617–622, 2002.
21. Selistre LFA, Cintra GC, Aleixo RD Jr, and Rosa SMMG. Relationship between extensor torque and H:Q ratio with triple hop distance in professional soccer players. *Rev Bras Med Do Esporte* 18: 390–393, 2012.
22. Xergia SA, Pappas E, Zampeli F, Georgiou S, and Georgoulis AD. Asymmetries in functional hop tests, lower extremity kinematics, and isokinetic strength persist 6 to 9 months following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 43: 154–162, 2013.

# Appendix IV: Participant Information Sheet (NIFS English)

(Research subject name)
Multiple hop testing: the diagnostic value to athlete profiling

Abstract of the research

1. This research aims to examine the multiple hop jump testing can be used to athlete profiling and how reliable it is.
2. We will measure 50m sprints, single leg triple hops and quintuple hops.
3. We will use force plates and inertial sensors attached at the sacrum and tibias. We also record them with video cameras.
4. We will have a practice for multiple hops before measurements. We also ask you to have particular worm-up to prevent injury.
5. If you have any question about the measurement or research please do not hesitate to ask us. You can suspend the measurement anytime. Please let us know when you want to do so.
6. You may not answer the question(s) if you do not want to answer the question(s).
7. Privacy of participants will be protected. The data will be used as anonymized.
8. This project is carried out by NIFS and AUT as a collaborative research.

Principal investigator:

Tomohito Wada
Associate professor, Information Technology Center for Sports Sciences,
National Institute of Fitness and Sports in Kanoya
Contact: 0994(46)4941, wada@nifs-k.ac.jp

# Research collaboration agreement

(Principal investigator)
Tomohito Wada
Associate professor, Information Technology Center for Sports Sciences,
National Institute of Fitness and Sports in Kanoya

(Research subject name)
Multiple hop testing: the diagnostic value to athlete profiling

I got an adequate and sufficient explanation about the research. I understood the purpose of the research, the human rights protection for the participants, the safety of research and I agree to participate to this research as participant.

Name：

Address：
Phone number：

(Date)　　　/　/

---

In case of the minority

Signature of guardian：

(Date)　　　/　/

# Appendix V: Participant Information Sheet (NIFS Japanese)

（研究課題名）片足跳び測定によるアスリートプロファイリングに関する研究

研究の概要

1. 本研究では，片足跳びがアスリートのプロファイリング（評価や予測）にどの程度有用か，また信頼性があるのかを検討することが目的です．
2. 50 m 全力走，3 歩片足跳び，5 歩片足跳びの計測を行います．
3. 測定は，腰と足首に慣性センサーを取り付け，フォースプレート上で行います．また，測定の様子はビデオカメラで撮影します．
4. 片足跳びは測定前に練習を行います．けがの無いように測定の前にはウォーミングアップを実施しますので，ご協力をお願いします．
5. 測定について不明な点があればいつでも質問してください．また，測定はどの時点でも中止することができます．中止したい際にはお知らせください．
6. 質問に対して，万が一答えたくない事項があれば回答する必要はありません．
7. 参加者のプライバシーは保護されます．測定したデータは個人が特定されない形で利用します．
8. 本研究は，鹿屋体育大学とオークランド工科大学（ニュージーランド）の共同研究として実施しています．

研究責任者：

鹿屋体育大学　スポーツ人文・応用社会科学系　准教授　和田智仁
連絡先 0994(46)4941，wada@nifs-k.ac.jp

# 研究参加同意書

（研究責任者の所属・職・氏名）
鹿屋体育大学　スポーツ人文・応用社会科学系
准教授　和田智仁

（研究課題名）
「片足跳び測定によるアスリートプロファイリングに関する研究」

私は，上記の研究課題の研究内容について適切かつ十分な説明を受け，その目的・被検者の人権擁護・研究の安全性等を良く理解しましたので，この研究に被検者として参加することに同意致します.

氏名：

住所：
電話番号：

（日付）平成　　年　　月　　日

---

被験者が未成年者の場合

保護者等署名：

（日付）平成　　年　　月　　日

# Appendix VI: Rater Information Sheet for Multiple Hop Kinovea Analysis

***YOU WILL REQUIRE A ROTATING MONITOR IN ORDER TO COMPLETE THIS ANALYSIS - THE PHILIPS MONITORS IN THE POSTGRAD ROOMS ARE SUITABLE**

1. Firstly, download Kinovea video analysis software for free at https://www.kinovea.org/en/downloads/ and install on your computer.

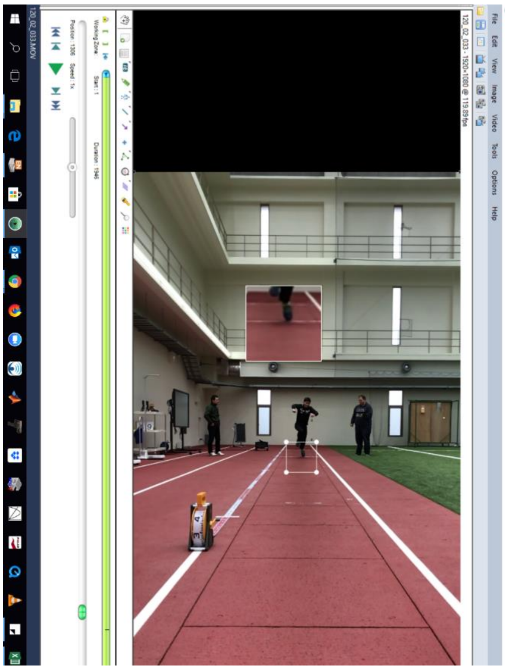
2. Open up Kinovea and locate 'Open Video File' icon.

3. Locate '**Subject 2**" folder, then '**29.01.2018'**, then open first file that is in the spreadsheet called '**120_02_033.MOV**'.

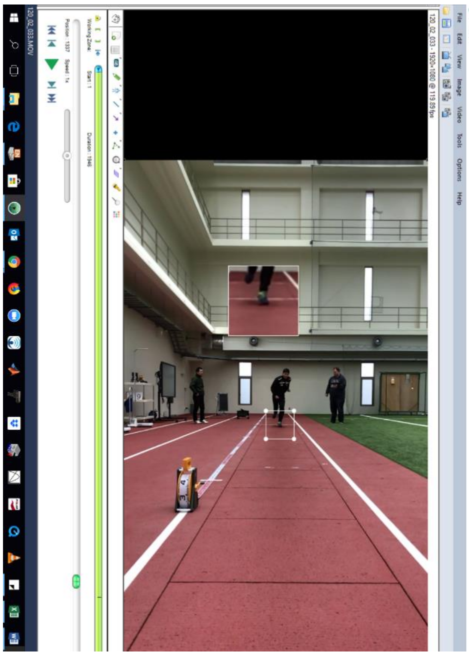
4. Locate the 'Green light on' position that is on the spreadsheet which is position frame **951** for the first trial, this will bring you close to the start of the trial.

5. A number of key events then need to be identified for 'toe off' and 'heel strike' for each hop. The nearest frame to the key events should be identified and the magnifying tool (2.5X) can be used for this if needed. Each video will only be either a left or right foot hops plus the last double foot landing.

   (a) Toe off – the **first frame** where the foot is **no longer** in touch with the ground.



(b) **Heel strike** – the **first frame** where the foot is clearly **in touch** with the ground.



6. Repeat for all hops and enter frame numbers in the spreadsheet.

# Appendix VII: Chapter 6 Supplementary Tables

**Table S1**. TH and QH kinematics descriptive data

| | TH Mean ± SD | | | QH Mean ± SD | | |
|---|---|---|---|---|---|---|
| **Variable** | **DOM** | **NDOM** | ***p*** | **DOM** | **NDOM** | ***p*** |
| Flight Time | | | | | | |
| Hop 1 | 0.283 ± 0.029 | 0.280 ± 0.033 | 0.335 | 0.276 ± 0.033 | 0.278 ± 0.032 | 0.359 |
| Hop 2 | 0.331 ± 0.045 | 0.333 ± 0.048 | 0.433 | 0.318 ± 0.046 | 0.320 ± 0.050 | 0.593 |
| Hop 3 | 0.442 ± 0.038 | 0.454 ± 0.035 | 0.002* | 0.331 ± 0.041 | 0.337 ± 0.046 | 0.160 |
| Hop 4 | | | | 0.344 ± 0.049 | 0.350 ± 0.048 | 0.069 |
| Hop 5 | | | | 0.452 ± 0.051 | 0.459 ± 0.050 | 0.084 |
| Ground Contact Time | | | | | | |
| Hops 1-2 | 0.287 ± 0.036 | 0.283 ± 0.030 | 0.313 | 0.277 ± 0.029 | 0.277 ± 0.032 | 0.935 |
| Hops 2-3 | 0.263 ± 0.030 | 0.260 ± 0.032 | 0.312 | 0.248 ± 0.028 | 0.246 ± 0.029 | 0.531 |
| Hops 3-4 | | | | 0.240 ± 0.029 | 0.242 ± 0.030 | 0.420 |
| Hops 4-5 | | | | 0.245 ± 0.031 | 0.242 ± 0.032 | 0.244 |
| Hops Times | | | | | | |
| Hops 1-2 | 0.611 ± 0.050 | 0.612 ± 0.048 | 0.959 | 0.593 ± 0.053 | 0.596 ± 0.054 | 0.581 |
| Hops 2-3 | 0.697 ± 0.040 | 0.708 ± 0.030 | 0.012* | 0.571 ± 0.045 | 0.575 ± 0.048 | 0.405 |
| Hop 3-4 | | | | 0.579 ± 0.046 | 0.588 ± 0.035 | 0.070 |
| Hop 4-5 | | | | 0.689 ± 0.055 | 0.699 ± 0.041 | 0.175 |
| Total Hop Time | 1.59 ± 0.104 | 1.60 ± 0.103 | 0.731 | 2.73 ± 0.161 | 2.73 ± 0.184 | 0.168 |
| Hop Distance | | | | | | |
| Hop 1 | 1.69 ± 0.157 | 1.69 ± 0.155 | 0.909 | 1.64 ± 0.161 | 1.65 ± 0.161 | 0.052 |
| Hop 2 | 2.05 ± 0.211 | 2.06 ± 0.200 | 0.523 | 2.00 ± 0.187 | 1.99 ± 0.162 | 0.975 |
| Hop 3 | 2.75 ± 0.304 | 2.75 ± 0.295 | 0.850 | 2.23 ± 0.202 | 2.24 ± 0.201 | 0.636 |
| Hop 4 | | | | 2.34 ± 0.288 | 2.34 ± 0.278 | 0.990 |
| Hop 5 | | | | 2.89 ± 0.391 | 2.87 ± 0.373 | 0.515 |
| Total Hop Distance | 6.44 ± 0.604 | 6.45 ± 0.590 | 0.731 | 11.1 ± 1.03 | 11.1 ± 0.977 | 0.727 |
| Reactive Strength Index | | | | | | |
| Hops 1-2 | 7.23 ± 1.44 | 7.29 ± 1.37 | 0.439 | 7.27 ± 1.24 | 7.34 ± 1.39 | 0.474 |
| Hops 2-3 | 10.6 ± 2.03 | 10.6 ± 2.12 | 0.671 | 8.97 ± 1.64 | 9.10 ± 1.69 | 0.269 |
| Hops 3-4 | | | | 9.97 ± 2.04 | 9.93 ± 2.13 | 0.774 |
| Hops 4-5 | | | | 12.2 ± 2.85 | 12.2 ± 2.85 | 0.976 |
| Total $RSI_{hor}$ | 11.9 ± 2.13 | 11.9 ± 2.14 | 0.484 | 11.1 ± 2.09 | 11.2 ± 2.19 | 0.464 |

**Key:** SD = Standard Deviation; Time variables = seconds; Distance variables = meters; RSI = $m.s^{-1}$; * significant difference between limbs *p*<0.05

**Table S2**. TH and QH kinetics descriptive data

| | **TH Mean ± SD** | | | **QH Mean ± SD** | | |
|---|---|---|---|---|---|---|
| **Variable** | **DOM** | **NDOM** | ***p*** | **DOM** | **NDOM** | ***p*** |
| Maximal Vertical Force | | | | | | |
| Hops 1-2 | 32.7 ± 5.01 | 31.5 ± 4.66 | 0.102 | 31.2 ± 3.79 | 31.5 ± 4.56 | 0.856 |
| Hops 2-3 | 40.7 ± 6.40 | 41.0 ± 8.28 | 0.724 | 40.0 ± 8.11 | 40.9 ± 9.14 | 0.477 |
| Hops 3-4 | | | | 45.0 ± 10.0 | 45.1 ± 9.21 | 0.739 |
| Hops 4-5 | | | | 50.1 ± 11.3 | 51.8 ± 13.2 | 0.491 |
| Vertical Braking Impulse | | | | | | |
| Hops 1-2 | 1.35 ± 0.634 | 1.27 ± 0.646 | 0.387 | 1.10 ± 0.641 | 0.992 ± 0.682 | 0.455 |
| Hops 2-3 | 2.55 ± 0.514 | 2.66 ± 0.544 | 0.255 | 2.06 ± 0.431 | 2.03 ± 0.486 | 0.722 |
| Hops 3-4 | | | | 2.74 ± 0.469 | 2.86 ± 0.431 | 0.169 |
| Hops 4-5 | | | | 3.51 ± 0.672 | 3.54 ± 0.587 | 0.483 |
| Vertical Propulsive Impulse | | | | | | |
| Hops 1-2 | 4.35 ± 0.415 | 4.39 ± 0.453 | 0.609 | 4.42 ± 0.488 | 4.56 ± 0.377 | 0.118 |
| Hops 2-3 | 3.31 ± 0.557 | 3.29 ± 0.567 | 0.781 | 3.52 ± 0.324 | 3.53 ± 0.397 | 0.630 |
| Hops 3-4 | | | | 2.82 ± 0.329 | 2.89 ± 0.325 | 0.468 |
| Hops 4-5 | | | | 2.44 ± 0.504 | 2.35 ± 0.654 | 0.286 |
| Horizontal Braking Impulse | | | | | | |
| Hops 1-2 | -0.051 ± 0.034 | -0.051 ± 0.032 | 0.964 | -0.029 ± 0.019 | -0.034 ± 0.025 | 0.091 |
| Hops 2-3 | -0.193 ± 0.052 | -0.196 ± 0.073 | 0.826 | -0.118 ± 0.050 | -0.114 ± 0.051 | 0.667 |
| Hops 3-4 | | | | -0.264 ± 0.050 | -0.256 ± 0.076 | 0.410 |
| Hops 4-5 | | | | -0.408 ± 0.125 | -0.407 ± 0.123 | 0.594 |
| Horizontal Propulsive Impulse | | | | | | |
| Hops 1-2 | 0.767 ± 0.149 | 0.745 ± 0.140 | 0.188 | 0.833 ± 0.130 | 0.814 ± 0.161 | 0.459 |
| Hops 2-3 | 0.527 ± 0.122 | 0.464 ± 0.102 | <0.001† | 0.599 ± 0.086 | 0.575 ± 0.099 | 0.098 |
| Hops 3-4 | | | | 0.459 ± 0.085 | 0.432 ± 0.078 | 0.040* |
| Hops 4-5 | | | | 0.370 ± 0.122 | 0.313 ± 0.086 | 0.002* |

**Key:** SD = Standard Deviation; Force variables = Ns.kg; Impulse variables = Ns.kg; * significant difference between limbs $p$<0.05; † significant difference between limbs $p$<0.001

# Appendix VIII: Supplementary Material for Chapter 7

**Sprint Test Protocol Instructions**

**1. Warm-Up Protocol**

Before beginning sprint testing, all subjects must complete the following warm-up sequence to ensure safety and consistency:

a) Light aerobic activity to raise core body temperature (e.g., jogging, skipping)
b) Dynamic flexibility exercises – lunges x 10, squats x 10, hamstring walks x 10, ankle hops x 10 (walk back recovery)
c) High knee skips with arm swings, horizontal bounds x 5, alternate bounds x 10 (walk back recovery)
d) 4 x 30 m sprints at 60, 80, 90, 100% (slow walk back recovery)

**2. Test Procedure**

a) The subject completes 3 x maximal sprint efforts over 50 m from a standing start position
b) The subject starts the sprint in their own time

**3. Rest Period**

Allow a minimum 5-minute rest between test efforts to ensure recovery and consistent performance.

# Appendix IX: Supplementary Material for Chapter 8

### Standardised Multiple Hop Test Protocol Instructions

### 1. Warm-Up Protocol

Before beginning any testing, all subjects must complete the following warm-up sequence to ensure safety and consistency:

- e) Dynamic flexibility exercises
- f) Upper limb dynamic stretches
- g) Lower limb dynamic stretches
- h) General movement
- i) Light aerobic activity to raise core body temperature (e.g., jogging, skipping)
- j) Explosive movement preparation: Perform progressive bounding exercises to mimic the explosive nature of the hopping tests

### 2. Test Description and Procedure

TH Test: The subject performs three consecutive hops on the same leg.

QH Test: The subject performs five consecutive hops on the same leg.

- c) The subject begins each trial balanced on one leg (the hopping leg).
- d) On command, the subject hops forward the required number of times (3 or 5 hops), using only the same leg for all hops (Fig 6).
- e) After the final hop, the subject must land with both feet.
- f) Use of the arms during hopping is allowed to replicate natural athletic movement patterns.
- g) Subjects are permitted to touch the ground with their hands after landing, provided the hopping foot does not advance further forward during or after the landing. This ensures that the maximum horizontal distance achieved is accurately recorded.
- h) The objective is to "reach the furthest horizontal distance in the shortest possible time."

### 3. Rest Period

Allow a 2-minute rest between test efforts on each leg to ensure recovery and consistent performance.

# Appendix X: Chapter Abstracts

## Chapter 2. Using Smartphones for Jump Diagnostics: A Brief Review of the Validity and Reliability of the My Jump App.

Jumping and hopping based tests can provide valuable insight into an athlete's proficiency in ballistic sporting movements like sprinting or change of direction. Capture and analysis of this are usually expensive, and laboratory based. Recent advancements in integrated smartphone video technology from the commercial space has led to an increase in their utility for sports performance and could be extremely useful to the strength and conditioning coach, but the accuracy and sensitivity of these are largely undetermined. This brief review discusses the accuracy of a smartphone video application called My Jump and its validity and reliability for jump-based diagnostics.

## Chapter 3. Videographic Variability of Triple and Quintuple Horizontal Hop Performance

**Context:** Horizontal hops can provide insight into how athletes can tolerate high-intensity single-leg stretch loads and are commonly used in athlete monitoring and injury management. Variables like flight, contact, and total time provide valuable diagnostic information to sports science professionals. However, gold-standard assessment tools (e.g., 3-D motion-capture, force-plates) require monetary and technological resources. Therefore, we used a tablet and free software to determine the between-rater, within-rater, and test-retest variability of the temporal events of multiple horizontal hop tests.

**Design:** Reliability study.

**Methods:** Nine healthy males (20.8 ± 1.3 years, 71.4 ± 9.8 kg, 171.7 ± 4.5 cm) across various university sports teams and clubs volunteered and performed several TH and QH horizontal hops over three testing sessions. Six raters detected temporal events from video to determine between-

rater variability, while a single rater quantified within-session and test re-test variability. The temporal variables of flight-time, and ground contact time for each individual hop, and the total time of each hoping series were determined. The consistency of measures was interpreted using the CVs and ICCs.

**Results:** Good to excellent between-rater consistency was observed for all hops (ICC = 0.85-1.00). Absolute (CV ≤ 2.0%) and relative consistency (ICC = 0.98-1.00) were excellent. Test re-test variability showed acceptable levels of absolute consistency (CV ≤ 8.7%) and good to excellent consistency in 10/16 variables (ICC = 0.81-0.93), especially those later in the hopping cycle.

**Conclusions:** A tablet and free digitizing software are reliable in detecting temporal events during multiple horizontal hops, which could have exciting implications for power diagnostics and RTS decisions. Therefore, rehabilitation and performance professionals can confidently utilise the highly accessible equipment from this study to track multiple hop performances.

## Chapter 4. Comparison of Multiple Hop Test Kinematics Between Force-Platforms and Video Footage: A Cross-Sectional Study

**Background:** Multiple hop performances have been assessed using force-platforms and motion-capture cameras. However, the accessibility of these technologies might be a hindering factor for many performance coaches. Currently, tablet devices are being used as alternatives to measure jumping and hopping performances.

**Objective:** This study aimed to compare multiple hop kinematics using the Kinovea application with force-platforms, the gold standard.

**Methods:** Using an observational cross-sectional study design, male athletes (n = 44; age 20.1 ± 1.4 years) completed TH and QH on force-platforms while being filmed using an iPad. Ground contact time, flight time and total time were analysed using Kinovea and compared with the force platform data.

**Results:** Statistical analysis showed a high level of agreement across all variables of interest but significant differences (flight time; -2.14 to -5.96 %, ground contact time; 4.89 to 5.83 %, total time; -0.37 to -0.58%) were observed across all variables of interest. A systematic bias for flight and ground contact times were seen for TH and QH.

**Conclusion:** The use of iPad and Kinovea application can be used as a valid alternative to measure multiple hop kinematics when performance coaches do not have access to expensive force-platforms or motion-capture cameras.

## Chapter 5. Stretch-Load Demands of Multiple Hops: Implications for Athletic Performance and Rehabilitation

**Purpose:** This study aimed to quantify the kinetic demands of multiple hops in series, a common exercise in athletic training and assessment. Focus was placed on comparing the demands of a QH task to a TH task, particularly focusing on any incremental stretch-load demands.

**Methods:** Forty-four male university athletes completed the hopping tasks across track-embedded force platforms to measure braking and propulsion kinetics.

**Results:** Statistical analysis revealed significant increases in maximal vertical forces and vertical and horizontal braking forces ($p < 0.001$) for both TH and QH tasks across steps. The last two hops of the QH task showed notably higher stretch-load demands than initial hops.

**Conclusion:** The findings highlight the biomechanical, stretch-load aspects of these exercises, which can help practitioners better prescribe and programme hops for injury prevention, rehabilitation, and performance enhancement.

## Chapter 6. Do Outcome or Movement Strategy Variables Provide Better Insights into Asymmetries During Multiple Hops?

Multiple hops performed horizontally in series effectively assess RTS readiness, as they mimic the propulsive and decelerative demands of sports. Movement strategy variables (kinetic variables) offer more insight into injury recovery than outcome-based measures (kinematic variables) like hop distance alone. This study focused on kinematic and kinetic variables to assess asymmetries during TH and QH tests with forty-four male athletes from university sports clubs and teams. The aim was to determine the magnitude and potential direction of asymmetry and compare the sensitivity of kinematic and kinetic variables. Results showed mean kinematic asymmetries below 7.1% (range: 0.00 to 28.9%), while average kinetic asymmetries were as high as 38.8% (range: 0.0% to 95.4%). These findings suggest that kinetic variables are more sensitive in assessing movement strategy, providing more detailed insight into rehabilitation and RTS decisions. The study emphasizes the importance of considering both outcome and movement strategy variables in injury recovery. These results have practical applications for clinicians and coaches supporting those in RTS scenarios, as well as those addressing performance deficits, therefore offering valuable information to refine exercise prescriptions and athletic program design.

## Chapter 7. Using Multiple Hop Assessments and Reactive Strength Indices to Differentiate Sprinting Performance in Sportsmen

Multiple hop tests are commonly used in both performance and rehabilitation settings to assess neuromuscular function. This study aimed to explore the relationship between hop performance and sprint ability. Specifically, it focused on three goals: (1) examining the connection between TH and QH distances and sprint performance and comparing the strength of relationship between hop kinetics and sprint times; (2) investigating two methods of calculating the TH and QH reactive $RSI_{hor}$ and their relationship to sprinting; and (3) assessing whether hop ratios or kinetic variables could distinguish sprinters of varying abilities. Forty-four male sportsmen participated, completing TH and QH tests and sprint times (5 m to 45 m) over 54x inground force platforms. GRFs were collected during hop trials and horizontal and vertical hop propulsive and braking kinetics were determined. Results showed strong negative correlations between hop distances and sprint times ($r = -0.700$ to $-0.796$), while kinetic variables showed weaker relationships with sprint performance ($r = -0.554$ to $0.017$). $RSI_{hor}$, derived from hop distance, correlated more strongly with sprint performance than $RSI_{hor}$ from flight time. Hop ratios (QH/TH) did not differentiate fast from slow sprinters, and maximal vertical force and horizontal propulsive impulse were the best predictors of 10 m and 40 m sprint times. These findings suggest that hop distance and $RSI_{hor}$ are valuable tools for assessing sprint performance and reactive strength.

**Chapter 8. Masterclass: Are You Getting the Most Out of Your Triple Hop Testing?**

The TH test is a widely used, practical tool that allows physical therapists to assess an athlete's RTS following injury. However, recent consensus statements have raised concerns that hop distance alone may be insufficient to capture the complexity of functional recovery or to fully assess inter-limb symmetry, potentially masking readiness and increasing the risk of re-injury. In this Masterclass, exemplar kinetic and kinematic data for the TH are detailed; the utility of the QH introduced; the distinction between outcome and movement strategy variables discussed within an asymmetry context; and, the integration of accessible, cost-effective technologies within a tier-based framework for RTS assessment outlined. The ultimate aim of the article is to enhance the evaluation of movement strategies and support clinicians in making more informed and confident RTS decisions.

# Chapter 9. Optimising Multiple Hop Testing: Practical Insights and Performance Implications in Physical Assessment and Training Design

Multiple hop assessments, such as the TH and QH for distance, are widely used to evaluate lower limb cyclic force production and inter-limb asymmetry, which help inform both performance and RTS decisions. However, hop distance alone may not fully reflect the underlying biomechanical integrity of movement, as it is influenced by various biomechanical components including joint kinematics, kinetics, neuromuscular control, and inter-segmental coordination. This 'new perspectives' article aims to: highlight the limitations of using hop distance as the sole measure; emphasise the importance of considering joint-specific contributions during propulsion and braking phases using exemplar data; outline the differences to consider when choosing a TH versus a QH; and discuss the integration of accessible, cost-effective technologies within a tier-based framework for athletic assessment. The ultimate aim of the article is to enhance the evaluation of movement strategies and support strength and conditioning coaches in making more informed and confident programming decisions.