Reliability and Validity of Kinetic Variables Collected on a Knee Extension Isometric Contraction, Using Load Cell Technology in a Healthy Population.

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ABSTRACT

Objective, data-driven assessments, specifically assessments which measure an individual's capacity or potential, are of increasing interest within the realms of physical medicine and performance. In physical medicine, this type of assessment typically includes aspects of tissue specific muscle force production (peak force) and various measures of muscular strength. These variables, while certainly valuable as a component of a tissue capacity examination, are limited when compared to domains of explosive-type force, or force produced in very short domains of time (<100-200 ms). While the concept of explosive force is commonly relegated to the world of sport and athletics, it is also extremely valuable in a variety of daily tasks, such as the maintenance of balance. Therefore, force variables, such as rate of force development (RFD) and impulse (IMP), within these time domains are being explored as influential factors of force profiling that could be useful in determining risk or recovery status after an injury. Unfortunately, the traditional process of collecting explosive force data requires specific technologies, most of which are expensive or impractical. The purpose of this thesis is to explore the use of a load cell device as an alternative to more traditional dynamometry for the purposes of quantifying explosive force. Acceptable outcomes of these studies would serve to support the use of the load cell device to enhance clinical testing capacities, ultimately improving the quality of diagnostic information provided to the clinician.

The overarching question that guided the direction of the thesis was: can a load cell device be used to collect kinetic data, as a clinical diagnostic tool, for the assessment of knee extension force output in a rehabilitation setting? This thesis explored variables of force production using the aforementioned load cell, with specific interest of explosive force, for the purposes of accuracy (reliability and validity). These studies involved the completion of three maximal, explosive, knee extension isometric contractions (at 60 and 90 degrees of knee flexion) within various unique protocols. These protocols, described as 'constrained' or 'unconstrained', were intended to proxy as versions of clinical use, and therefore were designed to incorporate a comparison of laboratory data collection and practical collection methodologies. The term 'protocol' was used to define five unique scenarios or layouts, incorporating varying degrees of fixation, constraint, and knee position.

The kinetic force variables included in this study were as follows: peak force (PF), peak rate of force development (PRFD), rate of force development (RFD_{2080}), and impulse (IMP_{2080}). The subscript

denotation, “2080”, corresponds to measures across a window of time that exists from 20% to 80% of peak force.

The first study determined intrasession reliability of the load cell device. The study included 32 healthy subjects (14 males and 18 females: age 31.8±7.91 years) compared across three trials completed in a single session. ICC inferences of medium to very high were found for protocol 1 and 3, the 90° knee flexion position, for all kinetic variables. These were notably higher than the 60 degree knee position. However, while the ICC values were high throughout for protocols 1 and 3, larger variability (CV%) were also found for RFD and IMP: (PF ICC = 0.97 to 0.99; CV% = 3.20% -4.50%), (RFD_{2080} ICC = 0.86 to 0.97; CV% = 10.5% - 17.9%), (PRFD ICC = 0.82-0.94; CV% = 8.90% - 13.4%), and (IMP_{2080} ICC = 0.85 to 0.98; CV% = 11.4% -20.7%). The second study determined intersession reliability of the load cell device. The study included 12 healthy subjects (6 male and 6 females; age 31.0±6.4 years) compared across three time points with 7-10 days between each testing period. When compared across protocols, PF was the only variable to demonstrate small and acceptable variability (CV’s being less than 1.5%, with the plinth at 90° protocol having <10% CV and >0.90 ICC for both testing sessions). The constrained version (protocol 1) was associated with lower variability of RFD_{2080} (the lowest CV being 10.1%), however, the unconstrained version at 90°demonstrated lower variability with PRFD (lowest CV% being 3.77, and highest ICC 0.83). Finally, study 3 focused on evaluating the validity of the load cell device comparing 26 subjects (12 males and 14 females; age 32.0±8.9 years) across all protocols including protocols collected using the isokinetic dynamometer. The isokinetic device represented the gold standard (constrained) protocol by which each of the other protocols were compared. With respect to the kinetic variables, no significant differences in means were identified between devices (P =>0.05), across all three protocols. Slightly higher means were noted with the isokinetic constrained protocol; however, these were non-significant. Only the 90 degree knee flexion position was explored based on the findings from studies one and two, noting a significantly improved reliability for the 90 degrees position compared to the 60 degree.

The findings of this thesis support the use of a load cell device for the purposes of obtaining kinetic variables within sessions and across various types of constraints (protocols), however it appears the 90 degree knee position is superior to the 60 degree position in terms of withing and between session reliabilities. Caution should be used when exploring PRFD, RFD, and IMP as these metrics appear to demonstrate questionably large variabilities (large CV%), especially in the cases of between session testing. In reference to Study 2, the use of the described procedures and protocols, cannot be recommended for between session testing for PRFD, RFD, and IMP. Although Study 3 highlighted the

consistency of the values across devices and protocols, the differences across sessions (Study 2) were not acceptable in regards to RFD/IMP/PRFD, and thus should be used with caution. The findings in this thesis support the use of the load cell device, in knee extension kinetic variables, for clinical practice and comparative analyses in the context of intrasession methodology, notably when collected at 90 degrees of knee flexion. It is recommended that future research further explore the intersession characteristics in an attempt to better understand and capture these kinetic variables for outcome testing and normative data profiling.

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LIST OF ABBREVIATIONS

RFD	Rate of Force Development
MMT	Manual Muscle Testing
HHD	Hand Held Dynamometry
APTA	American Physical Therapy Association
N	Newtons
Nm	Newton Meters
MVC	Maximal Volitional Contraction
ms	Milliseconds
PF	Peak Force
PT	Peak Torque
FTD	Force Time Data
EFP	Explosive Force Production
PRFD	Peak Rate of Force Development
RFD_{XX}	Rate of Force Development at Time Intervals
TPRFD	Time to Peak Rate of Force Development
ARFD	Average Rate of Force Development
IES	Index of Explosive Strength
IMP	Impulse
MU	Motor Unit
DD	Doublet Discharges
SD	Standard Deviation
CV	Coefficient of Variation
CI	Confidence Interval
ICC	Intraclass Correlation Coefficient
SEM	Standard Error of Measurement
RFA	Rate of Force Acceptance
PI	Primary Investigator

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DECLARATION

"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 where explicitly defined in the acknowledgements), 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."

_____

Christopher Michael Juneau

Date: 07/04/2021

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 nor material which to a substantial extent has been accepted for the qualification of any degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made. The student was the primary contributor (>80 %) of the research in this thesis. All co-authors have approved the inclusion of the joint work in this thesis.

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CHAPTER ONE - INTRODUCTION

Rationale and Significance of Thesis

As the innovation and evolution of medical management with musculoskeletal injuries continues to progress, the concept of reintegration and readiness have garnered increasing attention. This is rooted in the desire to help diminish the risk of reinjury, and to better profile a person's relative capacity for a given task, skill, activity, or sport[1-7]. While readiness and reintegration are popular terms used in the athletic population, these concepts are equally as useful and important in the general population, when considering tasks such as the ability to recover balance during an unanticipated perturbation or reaching quickly for a falling object[8-10]. Regardless of the population, a subject's performance profile should include a comprehensive battery of local and specific measures, such as muscular endurance or peak force production, as well as standardized functional movement tests, such as hop testing or single leg balance assessments[2-7]. These assessments typically include isolated tissue or joint performance objectified by a single maximal capacity of a contraction (peak force or torque) or the volume of repetitions completed at a given weight (muscular endurance). These data have demonstrated empirical value in evaluating a range of cohorts, from age-related strength changes in the lower extremity[11-13] to limb symmetry knee extension strength after anterior cruciate ligament reconstruction[14-16].

However, in recent years, there is an emerging interest in force-time characteristics and variables as they are more closely correlated with tissue capacity[1,2] and may provide better information about force production. In particular, rate of force development (RFD) - which force is produced as a function of time, and Impulse (IMP) - which rationales both the magnitude and duration of force, are both gaining clinical popularity[9]. With specific reference to RFD, it and its variants have been shown to provide better overall insight into the stiffness of the muscle-tendon unit[17,18], the physiology of the muscular unit[10,19], the capacity of the neural system[20-22], and psychologic confidence[1,23-26]. Moreover, increases in RFD have been associated with improvements in performance in numerous activities such as sprint speed and weight lifting capacity[27,28], along with tasks of daily living, such as increases in walking speed or sit to stand activities[29-31]. Thus, RFD and IMP measurements may be more valuable both when describing risk and readiness post-injury and when optimizing performance.

With respect to collection of RFD and IMP data, the force plate and isokinetic testing apparatuses offer excellent data collecting potential, have proved highly reliable, and stand as the golden standard for strength measures[32-34]. These devices are able to report a variety of kinetic data, including peak force, power, and impulse, which are extremely valuable, however, both devices are exceptionally expensive, compared to the hand-held dynamometer. They also pose a substantial problem in portability and

availability, as many are housed in testing facilities and thus not likely to be available for most coaches and performance staff. Sports performance and physiotherapeutic staff are lacking an affordable, portable, and clinically useful tool for which to adequately measure and track performance of force in the knee. While a variety or testing mediums and tools are available, the load cell offers a lower financial price point, more portability, and therefore potential higher utility for assessing this region. However, limited data exists with respect to reliability and validity of kinetic variables, such as RFD and IMP. This research evaluates the use of a load cell as a viable clinically practical alternative to an isokinetic testing device or a force plate in investigating kinetic variables, specifically in knee extension force profiling.

Purpose Statement

The overarching question that guided the direction of the thesis was: can a load cell device be used to collect kinetic data, as a clinical diagnostic tool, for the assessment of knee extension force output in a rehabilitation setting? The purpose of this research was to investigate kinetic variables, specifically PF, RFD, and IMP, collected by a load cell during a knee extension isometric contraction. This involved exploring these data in regards to intrasession and intersession reliability, and comparison against the gold standard, the isokinetic device. An ancillary aim of this research was to explore a novel method of statistical analysis for RFD and IMP, which offered a more automated approach to analysis and output. This would provide a more automated method for future studies and clinical use, and potentially improve clinical utility and methodology.

Study Aims

The specific aims of this thesis were:

1. To review current literature concerning the kinetic variables of human movement, and their impacts on injury risk, recovery from injury, and their value within a clinical setting.
2. To investigate if a load cell device could reliably and accurately be used to collect kinetic variables of a knee extension isometric contraction.

Thesis Outline and Structure

This structure of this thesis is provided in Figure 1 and is a hybrid between a traditional thesis and thesis by publication. It consists of a review of the literature (Chapter 2) which is written in a way that helps provide the author with all the necessary pre-requisite knowledge to understand certain aspects of the thesis direction and is not intended for publication. Three experimental investigations (Chapters 3-5),

however, have been written ready for publication. References for all chapters are included for the entirety of review and research at the end of the thesis. Chapter 1 is an introduction to the thesis highlighting the purpose and aims of this research project. Chapter 2 gives an overview of existing literature and is separated into three parts; a brief historical perspective on the force data collection in physical medicine, the second phase explores the shift away from peak force measurement into alternative kinetic measures and the value of kinetic data in force expression (specifically related to rate of force development and impulse), and the final section discusses force-time data collection device and load cell technology, with focus on its potential value in clinical practice of force acquisition. Chapters 3 and 4 present original research exploring the intra- and inter- session reliability of kinetic variables including RFD and IMP. Chapter 5 compared the kinetic load cell variables against an isokinetic device, representing the gold standard for kinetic data capture in isolated muscle environments. Finally, the sixth chapter discussed the findings of the thesis, highlighting the limitations, practical applications, and suggested areas for future research.

Figure 1: Thesis outline and summary

CHAPTER TWO - BACKGROUND

THE ASSESSMENT OF MUSCLE FORCE TESTING IN PHYSICAL MEDICINE: A REVIEW OF THE LITERATURE

Introduction

The process of profiling and measuring the capacity of physical performance has become increasingly popular, more robust, and ultimately more comprehensive. The advancement in technology, clinical understanding, and empirical justification has produced a growing desire for more objective and quantitative data related to injury risk, tissue capacity, and performance. This dramatic shift in technology-based data erupted in the 1970's and 1980's, and has radically changed how we evaluate the capacity of the human body[35]; it being primarily built around the efficiency of data collection, enhancing this process to deliver a readily consumable product[36]. Considering how valuable data can be, development and evolution of performance monitoring devices have also become a priority. The true novelty and merit of these devices are grounded in the cost, availability, and the ease of their user interface (the client and practitioner-facing processes of the system). This has produced a true paradigm shift producing substantial changes in the capabilities of data-based performance, evolving the process by which we evaluate and profile human movement and ultimately manage injury risk[37,38].

Unfortunately, the practice of physical medicine had shown fairly limited expansion in the use, integration, and application of data driven science around movement, strength, and risk profiling[39,40]. The American Physical Therapy Association (APTA), published a vision statement, titled: "Vision 2020", which served as a "call to arms" for the maturation of the profession, specifically citing evidence-based medicine as a priority[41]. This was fundamentally centered on bolstering the objectivity of the examination and intervention processes by implementing modern technologies in the interest of justifying reimbursement in the wake of changing healthcare policies[41]. While this vision was met with excitement, it became clear that the profession lacked the available research, resource, and clinical technology to develop into the modern era of data driven science[41]. This limitation led to evolution of new and attractive methods of data collection software, processing capabilities, and interface mediums[35], however, many of these devices were expensive, not portable, and generally impractical for clinic use. It has created an initiative to provide physical medicine professionals, such as physiotherapists, with tools which are user friendly, help synthesize and interpret data, yet are also cost-effective choices.

The intention of this review is to cover the mediums by which force production has been collected in physical medicine, specifically highlighting the limitations of each. The review will then discuss kinetic data within force production, including a synopsis of important kinetic variables, contraction types, devices for collection, and implications for their use in physical medicine. Finally, this review will highlight the paucity of practical, affordable testing tools for the purposes of kinetic data (specifically rate of force development (RFD) and impulse (IMP), and provide potential pathways forward for improving the practice.

Part I: Historical Perspective of Muscle Force Testing in Physical Medicine

The concept of force testing, as in the cases of muscle or muscle group performance, is a hallmark process in the realm of physical medicine. The domain of physical medicine should be considered as the realm by which musculoskeletal management is a major facet, being the professions of physiotherapy, chiropractic, athletic training, orthopaedic medicine, and others. In these professions, tissue capacity and force production strategies are a valuable component of practice, commonly used as a diagnostic tool, interventional treatments, and also as an outcome related tool[42-44]. Subsequently, practitioners in physical medicine have sought to develop and evolve methods by which to measure specific tissue capacity and force production capabilities which would be safe and graduated based on the tissue involved[42-44].

The process of force testing can arguably be traced back to Manual Muscle Testing (MMT), initially described in the late 1800's, and then popularized by Henry and Florence Kendall[42] in 1949. It has remained a staple through the 20th century in the examination of strength in physical medicine, despite its apparent shortcomings. MMT involves the use of non-invasive, manual resistance, observation, palpation, and force application by an examiner to determine the strength of a muscle action to evaluate neuromuscular integrity[42-44]. While a variety of MMT procedures have been described, manual pressure is provided to a moveable joint segment, and the capability of the segment to resist this external force is graded, typically on a 5-point scale[43], representing the individual's maximum force. The scale itself represents quasi-objective information, but the collection and interpretation of these data are almost entirely subjective and dependent on the rater's strength[43]. This scale was also not useful in athletic individuals as the force produced in this population was often beyond the capabilities of the tester, diminishing its value [45,46]. While these data were practical, the validity and reliability of such tests have failed substantially when explored and analyzed in experimental research, and very little evidence about responsiveness and interpretability exists[39,43,47-49]. MMT remains a hallmark of "strength" and force testing within physical medicine.

The evolution into testing technology led to the first objective force testing device, The Hand-Held Dynamometer (HHD), originating in the early 1900's[50-53]. It was among the first technology-based force data collection devices to receive popular use, and arguably still the most popular physical medicine testing device to this day[50-53]. While it was not immediately integrated into clinical practice and common utility, towards the early 21st century, the HHD became much more popular in clinical practice[50-53]. The HHD uniquely provided quantifiable force (muscle strength) data and was extremely portable, convenient to use, and generally affordable for most clinicians. These devices reported only peak, or maximal force, generally using no external software and providing no raw data. Also, concerns arose regarding its validity and reliability, being largely due to the testing set-up and methodology, not the device itself[47,50]. The device was being used in conjunction with MMT, as an extension of the tester's resistance, and therefore was subject to a myriad of testing errors[47,50]. Thus, a natural evolution occurred both methodologically (improving the consistency of the HHD procedure), and technologically (more scientific type of muscle force testing device, such as isokinetic muscle testing).

The progression of technology allowed for more intricate exploration of force and kinetic data, including avenues of muscular work and power. While the HHD continued to be popular, the exploration of new devices and procedures have begun gaining momentum. This included technology such as isokinetic devices, load cell technologies, and force plates. These devices, albeit substantially superior in their testing capacity and breadth, have seen limited integration clinically, largely due to issues of logistics; being that they may involve a large learning curve, be fairly immobile, and potentially beyond the affordability of many clinics and clinicians, therefore limiting their implementation. Ultimately, a need was created. It hinged on the ability to collect force data, beyond maximal force with a device that is more affordable and practical.

This review is not meant to be exhaustive for all testing devices and domains, but rather a brief exploration of the most commonly used modalities in physical medicine. Having discussed the historical perspective of tissue specific force testing, specifically in regards to the concepts, tools, and ideologies, "Part II" will further illuminate the genre of force collection variables, with specific interest in the kinetic variables of peak force and the domain of force time data (FTD). It will also begin to describe the genre of FTD and the nature of explosive force parameters.

Part II: Force Collection Methodology and Modes of Muscular Resistance

Tissue specific force testing can be collected in a variety of resistance modes, each offering both unique insight into performance capacity. Isoinertial testing, likely the most convenient and popular method of measuring force production, requires the application of set load or weight on the muscles throughout the range of movement, such as a repetition maximum bench press or squat. In this scenario, an individual's capacity is quite simply the maximal amount of weight completed for a given number of repetitions. This method is limited in its utility in physical medicine as it is inappropriate, and likely dangerous, during certain phases of rehabilitation[3]. It is also an inconsistent expression of force as the participants joint angle, muscle architecture, and gravity implications may change the experience of the individual throughout the movement arc[54-58]. Therefore, the testing component of this contraction is limited by the weakest joint position, and is not specific to joint angle, but rather specific to the exercise itself. An alternative to isotonic testing is isoinertial training, where inertia is maintained throughout the range of motion, thus producing a perceived resistance that is uniform irrespective of the joint position[54-58]. This type of testing is less common, and involves the use of specific equipment by which to maintain this force experience. Isoinertial contraction modes are not typically used for force testing purposes, however are more common in training[54-58, 69-72].

With respect to specific joint angle force testing, the two remaining muscle contraction avenues, isokinetic and isometric testing, can be utilized. Isokinetic testing captures joint specific force output throughout a joint range of motion, constrained by a given angular velocity. This is achieved through a dynamometer which is programmed to move at a defined angular velocity, while the participant attempts to produce a consistent maximal force output throughout the trial[54-58]. This process allows for the collection of force throughout a spectrum of joint angles within a single trial, assuming the participant produces maximal effort throughout the entirety of the trial. The corresponding output is a robust, and comprehensive, representation of objective force production (torque-angle) capability throughout the full joint excursion[54-58]. An issue with isokinetic testing relates to the ability to measure maximal force while the point of resistance is constantly rotating. The force/velocity curve typically shows decreases in force production capability as the angular joint velocity increases. Regardless of how slow the given angular velocity, the force production output will never represent the 'true' joint force capacity. Therefore, the process of testing for the absolute maximal force capacity would require a fixed joint position (zero velocity), known as an isometric contraction.

Isometric force testing has seen a relative renaissance as of recent[54-58], especially in muscle force profiling and other FTD. Isometric contractions are much easier to administer and set-up, require simpler and more convenient equipment and technology, and typically offer a more time efficient

testing methodology[59]. Isometric testing is safer to utilize in medical populations as it allows for self-regulation and is not dependent on angular velocity. It has been shown to be both reliable, and well-tolerated in populations where repetition maximum testing may be contraindicated[59]. Isometric testing metrics are also positively associated with athletic performances in tasks such as sprinting or jumping[9,60-64]. Isometric contractions offer the ability to emphasize specific joint positions, for both testing and training purposes. This can be used to explore specific positions of interest, alter length-tension relationships, or also highlight specific areas of pathology or weakness[9,60-64]. The isometric contraction involves minimal joint excursion which typically results in less fatigue and muscle soreness[9,60-64]. It can also be used in a variety of training intentions, ranging from strength to tendon loading, while offering an extremely portable and practical process[9,60-65]. Finally, an isometric contraction offers the most suitable contraction type to explore FTD, such as RFD and IMP, which are uniquely different to peak force (PF) values, and are receiving increasing interest for their roles in risk profiling, rehabilitation status, and performance[22,52,53,66].

Part III: Force and a Maximal Voluntary Isometric Contraction

A maximal voluntary isometric contraction (MVIC) offers the ability to measure a variety of kinetic variables, at specific and intentional joint angles, which can be extremely important in capacity and risk profiling[57,58,67,68]. This process involves force production characteristics as the muscle(s) are tested at varying lengths, or joint positions. Changes in force, and ultimately the value associated with various position testing, is the resultant of sarcomere length prior to contraction. This is the direct relationship of the magnitude of overlap between actin and myosin filaments[73,74]. This relationship is plotted as a length-tension curve, in which force magnitude is measured and reported, while angular velocity remains constant (zero) [75,76].

Joint position force testing, or more specifically the indirect interaction of length-tension and force production capacity, presents a nuanced debate which is built on a clinical question about the testing position; should the joint, or muscle(s), be placed in the position of: 1) greatest efficiency (e.g., the most optimal length-tension position to create force); 2) the position that is specifically related to injury (e.g., an end range position of the hamstring, hip flexion and knee extension, by which most hamstring injuries occur); 3) the position most similar to the task by which the testing of force is a surrogate (e.g., the “sticking point” of a bench press or squat); and, 4) the position representing the area of greatest deficit, or pathology (e.g., a knee extension MVIC collected at 90 degrees of knee flexion; the position of most discomfort in patellar tendon pain). An argument could be made for any, or all, of the above positions. Irrespective of the method, the true value remains in the comprehension and utilization of the

collected data, and the intention of the chosen method, should be justified. It is imperative that joint position (and length-tension) be considered when testing a given tissue across varying degrees of joint position, and comparisons across individuals should always consider interpersonal differences in anthropometry.

The most common variable collected with a MVIC is PF, representing the maximal force production capability for a given tissue at a given joint position. The subject or client is given indefinite time by which to produce the absolute maximal force possible, although no more than 3-5 seconds are typically required[22,28,59,69]. The value of PF represents the highest point of force within that trial, and thus does not describe the trial comprehensively. The measurement of PF has been the subject of concern, practitioners stating that it may provide only limited application in the evaluation of injury risk and be too myopic for transferability into performance[22,52,53,66]. It is well established that PF is associated with a variety of neuromuscular conditions, such as decreases with age[47,77] or after a stroke[47,78], and to a spectrum of post-surgical impairments[14,79-81] and performance variables[28,82-85]. It is also well accepted that a measurable, although non-specific, level of muscle strength is necessary for daily living activities[11,86], such as stair negotiation or placing items in an overhead storage compartment. However, reflecting on the time domain by which PF is produced, the amount of time generally required to produce PF (300 milliseconds or longer) is substantially longer than the time domain required to produce force during some daily and athletic activities (less than 250 milliseconds)[22,28,64,72]. In practical terms, if the rate of force production in recovering the lower leg as it trips over a sidewalk curb is longer than it takes the body to move towards the ground, then the person will be unable to prevent themselves from falling, regardless of the PF of the hip flexor muscle unit. While the muscular group involvement remains the same in both scenarios, PF is relevant only to the time domain by which it is allowed to be utilized in preventing the individual from falling down. Fundamentally speaking, the process of assessment, readiness, and capacity should better mimic the requirements of the task.

The process of risk and performance profiling is difficult, and it involves a network of components and interdependent variables. In many applications, PF will not provide sufficient information and thus, other characteristics of force production, such as RFD or IMP may be required. These two variables mark an area of increasing interest, collectively falling under the heading FTD.

Part IV: Force Time Data

FTD is a category of force metric, which considers the production of force in relation to time, often visualized as a force-time curve. This curve provides a substantially higher volume of information than

a peak force measure, and allows for force to be assessed over a time window. The multitude of force-time data points can help mediate errors in extraneous and outlying data points, and also give a more robust representation of contraction performance[44,50]. The category of FTD represents a wide array of variations, however, with respect to risk profiling and rehabilitation, a specific subset of FTD is becoming increasingly popular[64,87]. This subset is marked by the very early time domain associated with the production of force. It represents the ability to rapidly generate force, specifically focusing on the magnitude of force within a very short time interval (<250 milliseconds). Two variables within this domain, RFD and IMP, have seen notable appreciation in both empirical and clinical research as valuable factors in human movement capacity and functional profiling[1,88].

Although RFD and IMP are often considered together, they represent unique perspectives of force production. RFD is defined as the change in force divided by the change in time (i.e. the rate at which the contractile elements of the muscle can develop force), which translates practically into the ability of a motor unit to quickly develop force[1,61,64]. RFD represents the slope of a time interval within a force-time curve (Newtons/seconds), RFD = ΔForce/Δtime (Figure 2). IMP, is calculated as an integral of force with

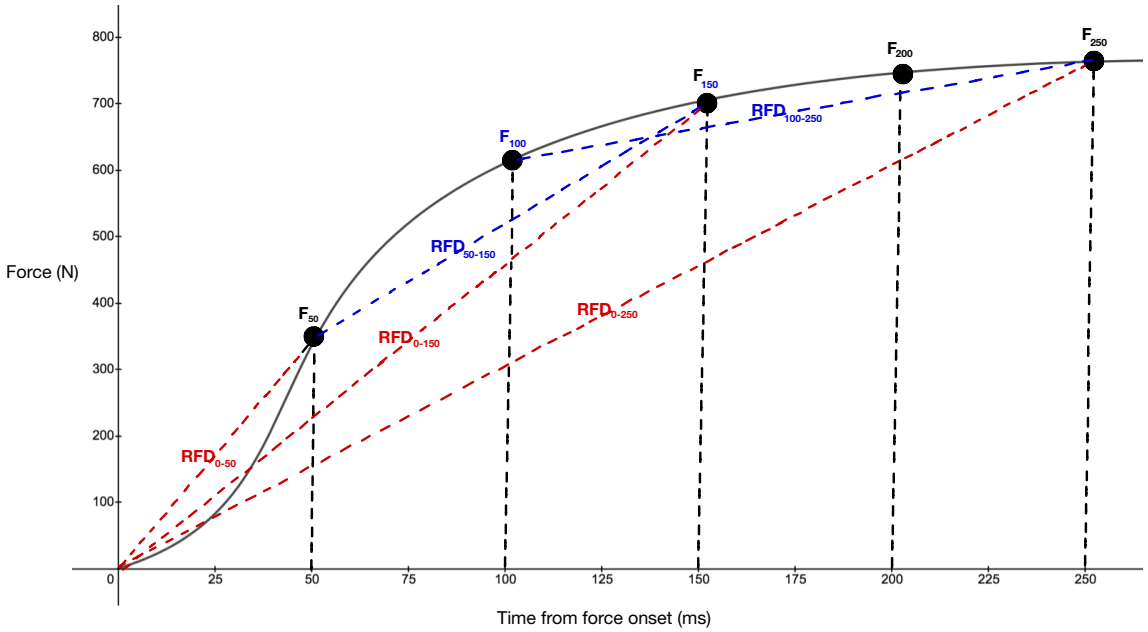

Figure 2: Graphical representation of a force-time curve showing various RFD intervals

respect to time, and represents the area under the force-time curve and is therefore recorded as Newton·seconds (Figure 3). IMP, like RFD, can be obtained for specific time intervals within a task or

force production trial[1,87]. IMP is valuable, in a practical sense, as it is directly related to the momentum of a limb or body (impulse-momentum relationship), and thus provides useful insight into performance capacity, beyond RFD or PF exclusively[87]. In clinical force interpretation, IMP is thought to be one of, the most important variables when interpreting force-time graphs[1,63,87,89].

While RFD and IMP have remained largely under-utilized compared to PF, they have been shown to provide better overall insight into the stiffness of the muscle-tendon unit[18,19], the physiology of the muscular unit[9,20], the capacity of the neural system[21,22], and psychologic confidence[10-13,23,24]. Moreover, increases in RFD and IMP have been associated with improvements in performance in numerous activities such as sprint speed and weight lifting capacity[14,15], along with tasks of daily living, such as increases in walking speed or sit to stand activities[46-48]. Therefore, RFD and IMP measurements may be a valuable diagnostic component when assessing function, optimizing performance, and describing risk and readiness post-injury.

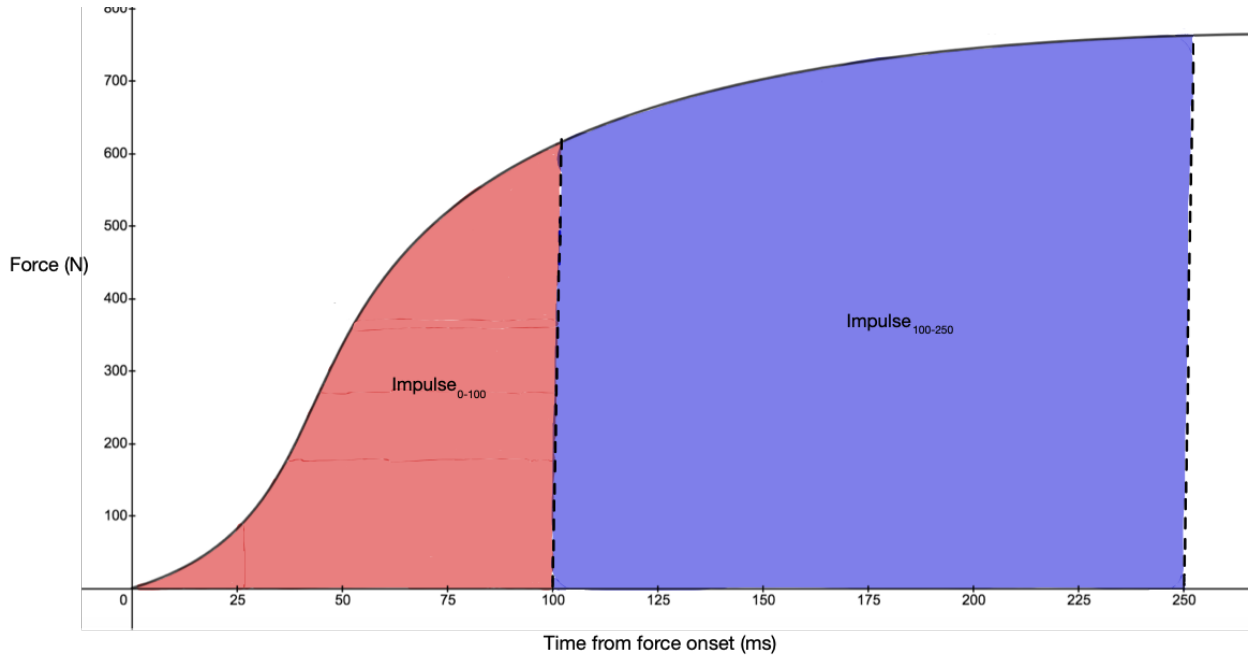

Figure 3: Visual representation of impulse (IMP) - newton·seconds

The concept of performance, as it relates to the completion of a given task, movement, skill, or sport relies on the collaboration of various inputs, ranging from neuromuscular efficiency, maximal strength, power, or perspectives of psychomotor patterning. The value of each variable is dependent on the specificity of the task itself, whether it necessitates high skill, a large force, a series of force productions, or an explosive force. In many scenarios, there is notable value in the capacity of maximal force as it is

well agreed that maximal strength is exceptionally important in the completion of movement tasks, risk assessment, and general health and wellness[90-93]. However, sport skills (such as throwing, kicking, and sprinting) and dynamic daily tasks (such as recovering from a perturbation, or catching an object as it falls from the table) involve motor unit recruitments in time domains of 30-200 ms, much shorter than the duration it takes to produce maximal force[89,94,95]. Therefore, in relation to these tasks, maximal force may not be entirely adequate. The rate of force developed within those constrained time domains ultimately defines the amount of force expressed and utilized. Ultimately, the value of RFD and IMP is not intended to supplant the role or value in maximal strength assessment, but rather provide a supplement in the description of the neuromuscular capacity within force production, specifically in instances of short time duration. Maximal strength will in many ways define the comprehensive ceiling of power production, while RFD will determine the effectiveness of the application of the force during explosive tasks.

RFD and IMP has been shown to be associated with a spectrum of tasks, including sprinting[96,97], jumping[90,98,99], change of direction tasks[100-102], throwing[103], weightlifting[104,105], as well as a group of endurance sports[106,107]. Jose Luis Hernández-Davó and Rafael Sabido (2014)[87] published a review of RFD and performance with a table that listed studies for which RFD (or variables of RFD) was shown to relate to various performance metrics. This publication highlighted the importance of RFD in athletics as both sport/task/movement specific, while also being related to the type of RFD metric utilized (various time intervals)[62]. As an example, Tillin et al. (2010)[108] demonstrated that high power athletes (jumpers and sprinters) demonstrate twice as much force during early phases of a muscle contraction, while only demonstrating around 20% greater maximal strength capacity[62]. Tilling et al. (2013)[9] also highlighted that RFD collected during a squat, specifically in the early phases of a contraction (<100 ms), were better correlated to sprint acceleration (r= -0.54 to -0.63), whereas later phase RFD (>100 ms) were more associated with vertical jump capability (r=0.51 to 0.61). The relationship of RFD and performance, however, it not entirely clear, as researchers exploring RFD collected via isometric contraction showed positive correlations between RFD and countermovement jump (CMJ) performance[12,109-111], while other studies have reported little to no association with the same two metrics[66,112-114]. RFD has consistently been shown to have significant relationships with sprint performance, specifically at the 5, 10,and 20 meter intervals[110,115], shown to have high correlations with maximal repetition performances in weightlifting (snatch, clean and jerk, and dynamic high pull)[116,117], while also being linked to cycling performance[118], running economy[119], swimming starts[110], and some promise as an indicator of footballers' performance levels[120]. This justifies the concept that maximal strength is necessary, but the extent is largely based on the time domain, in which case, the ability to express this strength is capital. It is clear, with the increases of RFD directed publications, that RFD is very much task/sport/movement specific and is likely

associated with a variety of sports beyond those mentioned above, and these relationships will continue to emerge with future research.

RFD and IMP have also been shown to be valuable factors in the completion of activities of daily living (ADL's), associated with improvements in quality of life[121,122], as well as an important consideration in advanced age, neurologically compromised, or at-risk populations[22]. It has been proposed, along with a currently evolving state of empirical data, that RFD can better predict functional abilities and difficulties than maximal strength assessments, especially in the case of inter-limb asymmetry[64,123-125]. These activities would include gait speed, which was noted by Suetta et al. (2004) to be more closely associated with capabilities of RFD rather than maximal strength in elderly individuals after hip replacement[124,125], as well as power production by the musculature of the back during lifting tasks[54]. RFD has also been strongly associated with prevention of falls, or the maintenance of balance, as the stabilizing process of the body occurs in very short, rapid contractions and not MVC's[64,108]. Slowness and/or poor control have overwhelming consequences on quality of life, independence, and general health in aging populations, therefore the capacity for 'quickness' in this cohort is extremely valuable[126]. It is likely that RFD plays a much larger role in other non-pathologic daily activities outside of what has been described, however, due to the paucity of current evidence in this avenue, the extent of its relationship is not entirely known.

Finally, RFD and IMP are associated with recovery from injury, as an aspect of rehabilitation and tissue/task readiness[127,128]. An example of this perspective would be recovery from a tear of the anterior cruciate ligament (ACL), which ruptures in the time domain of <50 ms[129]. Based on the rapidity of the injury, rehabilitation and reintegration after injury may benefit more from measurements of RFD and maximal force rather than maximal force, alone. Angelozzi et al. (2012)[22] explored the discrepancy between maximal isometric strength and RFD when compared at various time points after ACL reconstruction surgery. Angelozzi et al. (2012)[22] noted that average maximal isometric force was within 90% of their pre-injury levels, while RFD and IMP (taken at intervals of 30%,50%, and 90% of their maximal force production) was markedly lower (80%,77%,63%) than that of their pre-injury levels. These discrepancies were normalized at 12 months, but only after specific power-based exercise interventions. In similar fashion, individuals with a history of hamstring injury demonstrated statistically significantly less RFD (40% less) in the early phase when compared to their contralateral limb[130]. These reports appear to justify underlying RFD and IMP deficits, despite relative recovery of maximal force characteristics after injury. Joint degradation processes, such as those seen in osteoarthritis have been shown to demonstrate significant deficits in joint surrounding musculature, an

example being deficits in quadriceps function in those with knee osteoarthritis[131]. These deficits, which included maximal strength and RFD specifically in the case of knee function, have been negatively linked to a range of quality-of-life indicators, such as pain, disability, and progression of the disease process. It appears in many cases that RFD may provide better indicators of performance than maximal force[132]. Maffiuletti et al. (2010)[8] found similar results in a group of 150 individuals at six months after total knee arthroplasty and found an inter-limb difference in RFD (0-200 ms) of 36%, as compared to a 24% difference in maximal strength, while also highlighting that RFD was more related to subjective functional scores than maximal force. This agrees with the prior work of Gapeyeva et al. (2007)[133] who reported similar results in a smaller population of women after total knee arthroplasty, and Suetta et al. (2004) who found similar data on individuals after total hip arthroplasty[124]. These publications support the notion by Mizner at al. (2005)[134] that "diminished neuromuscular activation" is extremely impactful in the ability to complete various ADL's, such as stair negotiation and gait speed[8]. It is possible that the use of RFD can provide a more robust assessment tissue/muscle/neuromuscular function, or risk of re-injury, in these populations along with other sports injuries. It may provide more insight into the neuromuscular system and be more sensitive to acute or chronic changes in tissue capacity, while being associated with improvements in self-reported physical function activities and physical performance[135,136]. RFD represents a component of IMP, and therefore it is also likely that IMP would play a major role in the above listed movements, activities, and tasks, however, limited evidence on IMP specifically exists at this time.

Part V: Variations of RFD and IMP

The previous sections have used the terms RFD and IMP in a general sense, based on the mathematical definitions, however, notable variations and types exist within these genres. Firstly, RFD and IMP can be obtained during any type of movement (dynamic or static) and with any type of muscle contraction (isometric, concentric, or eccentric), although RFD/IMP is most commonly reported during isometric contractions, as it is a more consistent form of measurement[1,61,63,64]. Secondly, RFD/IMP can be calculated for any specific point or any defined time interval within a force-time curve. As these intervals reflect different points within a muscular contraction, it becomes imperative that the time interval be identified and labelled consistently as RFD/IMP will change depending on the point for which it is measured. For this reason, RFD/IMP should be labelled as RFD_x/IMP_x (which assumes the trial it from the onset of the contraction to the point labelled in the subscript) or RFD_{xx}/IMP_{xx} (which labels the exact time points for which the RFD/IMP corresponds). The process of selecting these epochs, or time intervals, therefore becomes very important in the accuracy and consistency of the data and how it is reported. The intention of most RFD/IMP data is to describe the capacity for explosive

development of force, the trial duration is reserved to extremely short time intervals close to the initial onset of the contraction[1,61,64]. These exceptionally short time intervals correspond to the time domain of explosive tasks, such as plyometric hopping, sprinting, recovery of a loss in balance, or reaching abruptly for a falling object, which can be completed in a little as 100 to 250 milliseconds[26,31,61,64,137]. For this reason, the maximum time window for most RFD/IMP data collection is 500 milliseconds[1,87,137], beginning with the initial onset of contraction. RFD/IMP would then represent the rate of change in force over the time of the testing window, or a sub-divided interval within. Figure 2 provides a representation of RFD for a variety of time intervals, while the corresponding IMP could be measured by calculating the area under the created interval.

The aforementioned example of RFD/IMP, RFD_x/IMP_x, represents one of a variety of types of RFD/IMP. The most commonly utilized and described types of RFD/IMP are Peak RFD (PRFD), RFD/IMP at specific intervals of time (RFD_x/IMP_x), and time to peak RFD (TPRFD) as these have shown the most significant clinical and performance value[1,23,61,64,138,139]. PRFD, represents the steepest slope, or highest RFD, within a predetermined series of sampling windows. These windows, logically, can be stratified by any time duration and could contain any number of epochs, however, it is most common that these windows are allocated every 20 ms or 50 ms, as these time intervals have been shown to be more reliable than longer or shorter intervals[4,527,88,140-143]. In the case of describing PRFD for the sampling windows, the PRFD is calculated for each interval, and the highest RFD is labelled $PRFD_{xx.}$ Similar to PRFD, RFD at specific interval ($RFD_{xx)}$, where the subscript identifies the interval for which the RFD corresponds, simply describes the ΔForce/Δtime for any epoch. The important delineation between these two variables, PRFD and RFD_{xx}, is that that PRFD is more focused on the peak value of the pool of samples chosen, rather than simply describing the value within a certain epoch. If the intention is to explore specific time intervals, such as those epochs associated with specific movement tasks or explosive movements, it may therefore be more valuable to explore the initial 0-250 ms window, divided as 0-50 ms, 50-100 ms, and onward. Thus, it would be possible to both describe the interval at which the highest RFD occurs (PRFD), but also compare the individual's performance at specific windows, against other individuals, other trials, as outcome tools, or with respect to specific tasks (RFD_{xx}). Once PRFD is established, it is possible to then determine the time from onset of the contraction to the PRFD produced, termed time to PRFD (TPRFD). This is specifically useful as it provides information about how quickly the individual is able to achieve his/her PRFD within a movement[66,144]. Table 1 provides an example table of PRFD, TPRFD, RFD_{xx}, and PF as it would be computed.

Table 1: Example of a force-time trial reported in 50 ms epochs demonstrating RFD, PRFD, and TPRFD

Time (ms)	Force (N)	Change in Force (N)	Change in Time (sec)	Change in Force/ Change in Time ($N \cdot s^{-1}$)	RFD ($N \cdot s^{-1}$)
0-50	50	50	0.05	50/0.05	1000
0-100	175	175	0.10	175/0.10	1750
0-150	250	250	0.15	250/0.150	1666
0-200	400	400	0.20	400/0.20	2000
0-250	550	550	0.25	550/0.25	2200
				PRFD	2200
				TPRFD (ms)	250
				PF	550

PF = Peak force; PRFD = peak rate of force development; RFD = rate of force development; TPRFD = Time to Peak RFD

Part VI: The Underlying Neurophysiological Factors of RFD and IMP

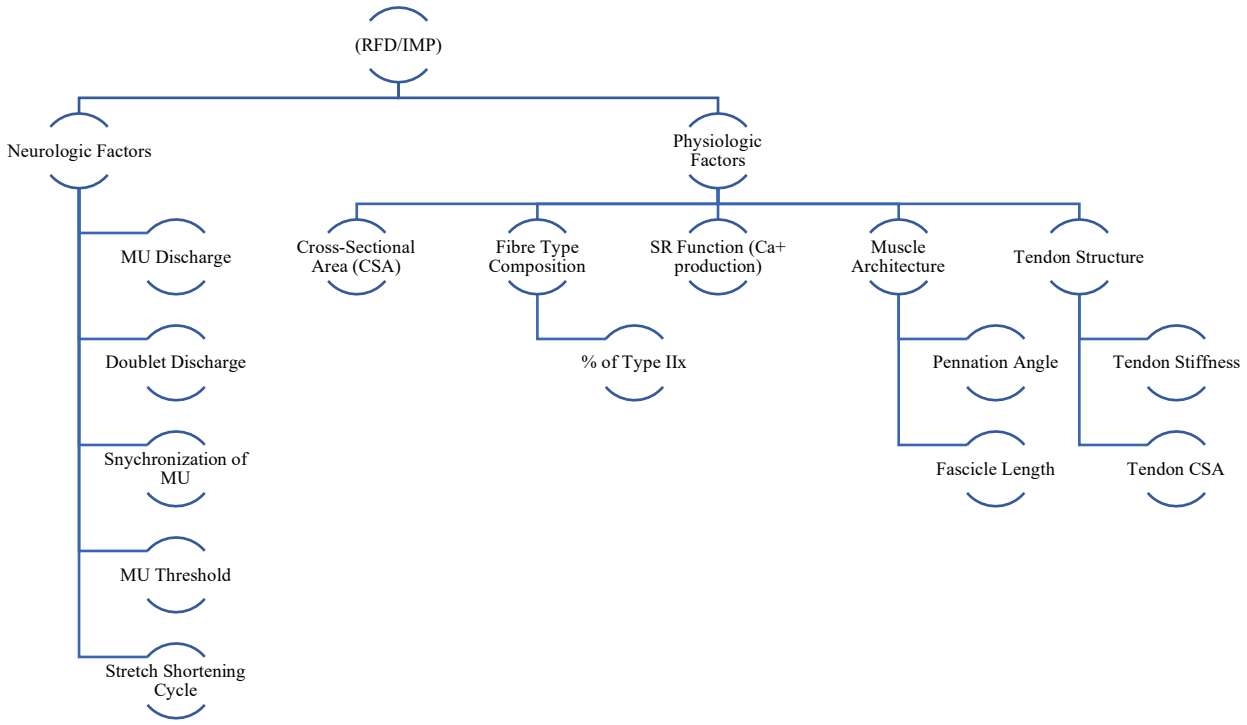

Figure 4: Neurophysiologic factors that may influence RFD/IMP (Adapted from Rodríguez-Rosell 2018)

The neurophysiologic process of muscular contraction capacity is an extremely complex process (Figure 4), which incorporates a concert of structural and neuromuscular factors[87,144]. As RFD describes force as a variable of time, the magnitude and speed of the muscle shortening process will have significant impacts on performance of maximal force production as well as with respect to the rate of contraction[144-146]. It is empirically accepted that changes in rate of force are correlated with three types of neuromuscular changes, namely changes in neural drive[19,147], muscle fiber type or type percentage[9,18,108], or muscle-tendon stiffness[17,148]. As multiple studies have explored and described, the pathway and collaboration of each individual component may vary quite substantially which may explain the significant differences in RFD in samples and groups described as highly homogeneous[99,108,146,149]. Therefore, it is prudent to describe and understand these underlying components and their role in the process of explosive force production data.

Neural Factors of RFD

Viitasalo and Komi[150], in 1981, highlighted the concept that a rise in motor unit activation was associated with a rise in force production, therefore identifying the neural input as a major role player in force production, explosive force, and subsequently, power. It is likely an intricate concert of neurologic variables that are responsible for this phenomenon, however, the concepts of rate coding, synchronization, and doublet discharges appear to have the largest impact.

Rate Coding

The rate of motor unit (MU) discharge, also known as 'rate coding', appears to play one of the, if not the most, important role in production of RFD, specifically RFD in the early or initiating phases of a contraction[151,152]. Rate coding describes the frequency by which the MU discharges and, in collaboration with the total number of MU's which are activated (MU recruitment), ultimately dictates the force produced by the contraction of a muscle[20,151-156]. However, depending on the intention of the movement or contraction, the contribution of rate coding versus MU recruitment may vary, and therefore play larger or smaller roles. Speaking specifically in terms of RFD and PF, various studies have reported significantly higher motor unit discharge frequencies (around 200 Hz) during assessment of maximal RFD, versus assessment of PF (around 15-35 Hz)[20,156,157]. Therefore, it has been suggested that neural factors in rapid force generation, specifically supramaximal rate coding capacities, are extremely important in the initiating phases of a muscular contraction, especially those seeking to produce high RFD rather than PF[156,159]. It was also proposed that rate coding plays a role within RFD, specifically regarding the initial contraction phase (<75 ms). This further supports the statement that the neural input, efficiency, and discharge rate offer the most value in terms of explosive force production

in the very early phases of a muscular contraction aimed to produce RFF. It may be the simple result of a limitation in force capacity, or it may involve a collaboration of various motivating, contraction coordination, and task concentration-based variables, which all seem to impact force production[1,156]. These unknowns may explain the inter-person variability in muscle activation and force production during explosive contraction metrics such as RFD[13,72,149].

Synchronization and Doublet Discharges

The process by which an individual is able to both produce and maintain a smooth contraction is controlled by their ability to synchronize the activation/deactivation processes of corresponding motor units[160-163]. It is possible to improve this process of two or more motor units firing at once, with heavy strength-based training programs. Strength training has been shown to increase the number of units synchronized and lower the force threshold to synchronization, which improves the process of muscle activation, thereby improving force[160-163]. Typically, low levels of intensity will be accompanied by asynchronous motor unit activation, whereas higher intensity or explosive intent (ballistic) will begin to produce more synchronization of the motor units[95,149,158]. Along with rate coding and motor unit synchronization, the concept of doublet discharges (DD) has also been proposed as a neurologic factor in RFD. DD describes a behaviour in which two action potentials occur within an extremely short period (interspike interval of less than 5 ms)[20,164]. This is believed to be the product of delayed depolarization in spinal motoneurons[165] and an increase in calcium release by the sarcoplasmic reticulum[166,167], which results in a substantial rise in force production. Although the exact mechanism behind this phenomenon is not entirely understood, empirical evidence has linked incidence of DD's to significant increases in RFD, impulse, and maximal force development[20,147,159,164,166,168,169]. Interestingly, it is also been reported to be a unique factor in maintaining force production after sustained muscle fatigue. DD is also both adaptable and trainable, positively stimulated by ballistic training programs focused on rapidity of movement. Van Cutsem et al.[20] demonstrated a change in DD incidence from 5% of MU's to 33% of MU's in response to a 12-week high speed strengthening program. DD has since been found to be an important variable in RFD in aging populations, who show decreased RFD and DD throughout later stages of life[13,169]. These studies demonstrate the value and unique quality of DD in the development of sustained force under fatigue, efficiency of MU recruitment, but also its value within early intervals of MU contractions[164,170].

Elastic Energy (Stretch Shortening Cycle-SSC) and the H-Reflex

The use of the SSC and reflexive contraction can be used to alter force production capabilities[171,172]. This process, which incorporates the use of a plyometric muscle action (an eccentric or muscle

lengthening contraction followed quickly by a concentric muscle contraction), has been shown to significantly improve force production[171,172]. This concept is thought to involve a group of factors such as invoking the stretch reflex and optimization of the length of the muscle[172,173]. There is also some evidence that maximizing muscle strength is linked to improvements in the concentric phase of the SSC and therefore of value in explosive force production and RFD[171]. Finally, the use of the Hoffmann reflex (H-reflex) has been shown to increase the force output capacity in some cases. The H-reflex describes the reflex system that is similar to that of the spinal stretch reflex, which corresponds to excitability of the motor units[159,176]. Unfortunately, the exact understanding of this process in force development is not completely known at this time, but research is developing and exploring further into this process as a medium to better highlight the neurologic components of force production.

Structural Factors of RFD

In conjunction with neural facilitative factors, structural variables also play a vital role in the comprehensive process of rapid force, specifically in the later phases of RFD, as discussed above.

Muscle Fiber Composition

Muscle fiber type or composition (myofiber phenotype), as it relates to the ratio of type II to type I fiber, is thought to be the most impactful structural variable. It is well known that the properties of type II, especially type IIx muscle fibres produce a larger maximum shortening velocity and force output than its "slow-twitch" counter parts, type I[1]. Type II fiber types boast larger, and faster, amounts of calcium with each action potential[177] along with fast communicating components (myosin, troponin, and tropomyosin)[178,179], which yields more rapid cross-bridge cycling rates (4-9 times faster than type I)[1,180,181]. It appears a moderate-strong correlation exists with the presence of higher type II fiber and RFD[26,149], noting that the neural dynamics, described above with rate coding, are accentuated in tissues that are more suited for rapid shortening. In conjunction with fiber type composition, the relative size, or cross-sectional area (CSA), of the contractile unit has also be linked to changes in RFD[19,123,124,159,182]. Studies have shown positive correlations with CSA and RFD, as well as demonstrated adaptive changes in both force output, RFD, and CSA throughout a periodized strength program[109,124-126137]. Therefore, it is very plausible that a notable percentage of RFD capacity is related to the CSA of the muscle tissue, specifically to CSA with more advantageous fiber composition percentage (type IIX > Ia). Interestingly, with respect to CSA, muscle architecture appears to play some conflicting roles with RFD and CSA[26,64]. Larger pennation angles are associated with larger, more broad, physiologic area and thus more CSA, however the increased pennation angle also transfers into a less direct line of force transmission,

therefore potentially reducing RFD[1,63]. Further exploration into this area is needed, specifically the mechanisms by which RFD is impacted by pennation.

Stiffness and Compliance

Tendon stiffness, corresponding to the compliance, represents the resistance of an elastic body to deflection or deformation by an applied force[183-185]. Young's Modulus defines the relationship of stress and strain with respect to a material, and ultimately in the context of the human body, is a proxy for efficiency of force transfer from the MU to the movement segment (bone). As the concept of human movement involves three distinct tissues (muscle, tendon and bone), the stiffness of each of these three materials is relevant. Bone is rigid, and thus highly stiff; however, muscle and tendon tissue can exhibit larger discrepancies and therefore have a greater influence on force transfer. Any loss of force transmission will be expressed as a loss in force capability, which is particularly important in explosive movements[1,87]. In these cases, optimal efficiency is required more than the cumulative process of maximal force, which can overcome this loss of force transmission throughout the longer duration. Elastic properties of muscle and connective tissues have been reported to account for around 40%-60%[186] of the force rise in early phase contractions, and should therefore be considered in the realm of RFD/IMP and explosive strength metrics[1,187]. The variables of stiffness in muscle are associated with elastic "slack" found within the muscle fascicles or within a series of muscle tissue. This can be a product of tissue architecture (specifically the pennation angle), or the fascicle length, the longer fascicle length having more elastic and less stiff properties. However, the impact of MU compliance accounts for only a portion of the deviation in explosive force, highlighting the significant influence of other important components, specifically the aforementioned neurologic system and the tendon complex[1,63]. PRFD, more specifically PRFD in the initial to middle ranges of a rapid contraction, has been associated with aponeurosis–tendon stiffness[1,63,188]. The exact mechanisms of tendon stiffness remain controversial at this time, being attributed to CSA changes, interfascicular factors, and cellular mediators[1,63,188]. Irrespective, the impact of tendon stiffness on RFD is valuable, accounting for around 30% of the variance documented during isometric RFD knee extension testing[188], and should be considered when describing RFD/IMP.

Summary of Neurophysiologic Factors of RFD/IMP

The neurophysiologic process of rapid, explosive force cannot be attributed to any singular variable, although it appears that some variables are more impactful than others, namely the influence of the neurologic rate coding, muscle fiber composition, and the stiffness of the tissues involved. At this time, the empirical evidence recognizes the collaborative process of RFD/IMP, but the exact contribution of

each variable with regards to RFD/IMP remains unknown, and it is becoming more empirically plausible that the collaboration of neural and physiologic interactions may vary in regards to various phases within explosive force data[26,31,64,159]. If this framework is accepted, it appears that the initial phase of RFD/IMP, within the first 75-200 ms, is overwhelming directed by the neural drive and physiologic components[26,31,64,159], while the latter phases of RFD, 200-500 ms, would be more facilitated by maximal strength capabilities[26,63,188]. Early phase RFD/IMP (< 100 ms) is primarily controlled by the input of the neurologic system (50%), the twitch response (15%), and finally input of maximal strength capability (20-25%), while mid to later phases are primarily governed by maximal force (50%)[62]. These factors, both neural and physiologic, represent modifiable and adaptive characteristics, therefore representing trainable variables. This can be accomplished with focused ballistic movement, explosive based strength training, heavy strength training, or any combination of these as each variable would, in theory, influence specific characteristics of RFD/IMP. As more evidence evolves of both a 'synergistic and multiplicative relationship' between the neurologic and physiologic inputs, specific recommendations can be made regarding training.

Part VII: The Methodological Considerations of RFD and IMP

The methodological process of collecting RFD and IMP can be quite nuanced and create substantial issues in the reproducibility and accuracy of the data (Figure 5).

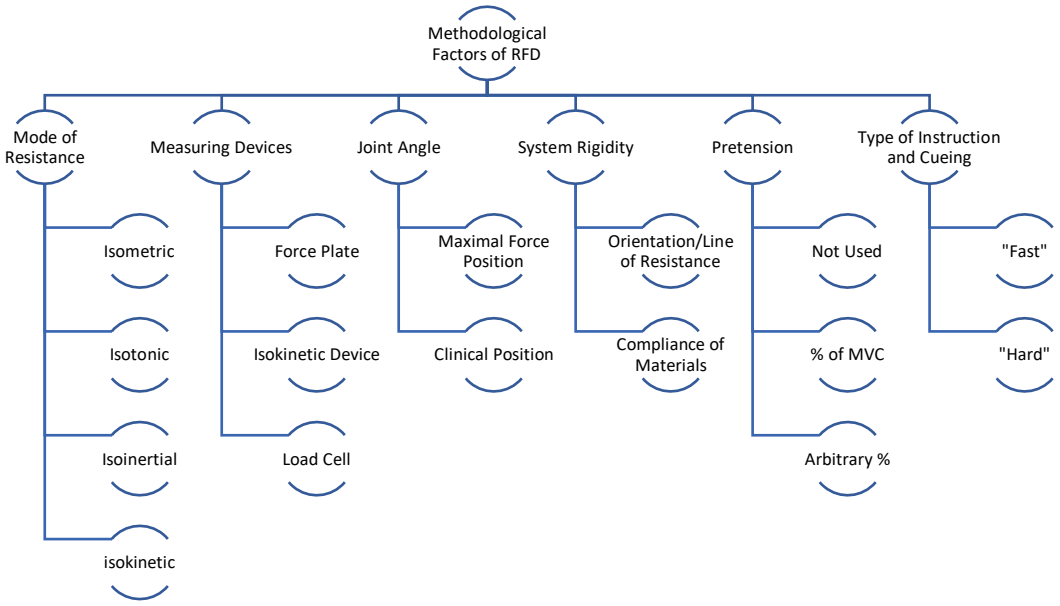

Figure 5: Methodological factors that may influence RFD (Adapted from Rodríguez-Rosell 2018)

Task and Type of Muscle Contraction with RFD and IMP

RFD/IMP can be collected in both static (isometric) and dynamic environments. Isometric force collection is precise, constrained, but only descriptive of a single joint angle and therefore mover (muscle), while dynamic force data represents a more realistic and more practical assessment, but includes larger variance and less constraint. The selection of testing procedure is, therefore, largely based on the task of interest. Many researchers initially chose to explore RFD/IMP during isometric contractions due to the higher level of control and constraint, which produced acceptable and high reliability[9,60-64]. However, this benefit comes at the potential cost of its limited external validity to functional movement tasks, and also only represents a specific range (in terms of length-tension of the contractile unit) of force production capability, while dynamic RFD/IMP, measured during multiple-joint movements, such as squats[9,189], leg press[19], and mid-thigh pulls[59,66,190], will provide a more transferable representation of force. While limited research has explored the relationship across types of contractions[9,88,140], it appears that changes in contraction type or movement can produce large, unacceptable, variances in RFD/IMP. As evidence evolves, a better understanding may allow more accurate recommendations around comparing RFD/IMP across contraction types, however at this time, it should be highlighted that modes of contraction will incur large deviations in data and cross-comparisons should be avoided[63,88].

Collection Devices and Sampling Rate

A variety of devices can be used to collect RFD/IMP. These include the aforementioned force plate technologies[66,88,123,141,191,192], commercial isokinetic dynamometry devices with a rotational torque transducer[19,26,64,124,193], and linear load cell devices[66,108,137,194]. Each device offers unique advantages and disadvantages, some being better suited for dynamic versus static testing procedures, while other devices are more clinically practical and financially feasible.

The force plate and isokinetic devices stand as gold standards in their respective areas of assessment. The force plate is a collaboration of force transducers, which are used to measure ground reaction force[195,196]. The type of force plate, along with the capacity of its data collection, is dictated by the composition of transducers, both in type of transducer and number of transducers. One of the most commonly used transducers, a load cell (or strain gauge) utilizes a change in electrical current as a response to the deformation of an associated material[196,197]. As the force plate and load cell devices are often used to explore high velocity, or explosive, forces such as those seen in running of jumping, or used to explore very small epochs within a movement, the sampling rate required is high.

The sampling rate of a device represents the frequency at which data points are collected within one-second, expressed in Hertz (Hz). The higher the sampling rate, the increased precision and number of data points collected for a trial. Most researchers, when exploring movement and force, especially in small epochs or explosive movements, recommend the use of at least 500 Hz[198], while some support that human movement research should be around 1000 Hz[199,200], as sampling rates below these thresholds can lead to misrepresentation of the true peak force by the data[201]. Most force plates are more than capable of achieving this sampling rate; however, this is not always the case with the isokinetic devices that have a variety of sampling frequencies depending on the model or type. Older models sample at an adequate rate to quantify peak force, however, this is too low for RFD (around 100 Hz[202]).

Isokinetic dynamometry is a method of force testing which employs the use of "hydraulic or electromagnetic instrumentation, which can be used to impart constant angular velocity"[203]. It stands as the gold standard of dynamic, joint specific, force data collection in physical medicine. It requires the tested individual to be constrained in a device, while the joint being investigated is aligned with the rotational axis of a dynamometric arm. The moving dynamometer arm resistance is equal to the muscular force produced against it throughout the arc of motion, essentially allowing the measurement of force during a dynamic activity. The angular velocity can be changed, along with the angular displacement, to accommodate to specific ranges of joint motion or different angular velocities. Despite the ability to measure a variety of force-time data, the most commonly reported information is maximum torque (with associated joint angle achieved), torque output at different angular velocities, the torque ratio of reciprocal muscle groups, and the torque output during repeated contractions[203,204]. Empirical evidence has substantiated its reliability (good to excellent) within tests and between devices[202,205-207], however this is exclusively regarding isokinetic peak force, with work and power demonstrating slightly less reliability, and a relative paucity of reports regarding RFD/IMP[202].

RFD/IMP is most commonly captured during static, isometric contractions[63,64,188], for which the isokinetic and load cell are more suitable options, the latter boasting a substantially lower price point and increased overall portability than both the force plate and isokinetic device. Both the isokinetic device and force plate are largely immobile devices, requiring financial commitments of thirty to forty thousand US dollars, well beyond the capability of most clinicians. In regards to accuracy of the data collection in compound, dynamic movements (such as a jump or push up), the isokinetic device cannot be used outside of its housing, and thus, is limited in its applicability. For this reason, the use of the force plate is suggested as the primary option for RFD/IMP in dynamic multi-joint or multi-planar contractions. The use of force plate has been shown to be superior beyond the capacity of the load cell, however,

innovations in testing methodology (such as those seen with the mid-thigh pull set-up) are seeing load cell devices becoming viable options[190,208].

In summary, when exploring RFD/IMP in multi-joint movements, the force plate or load cell stand as the recommended devices. The isokinetic device offers the better option for acquisition of PF within single joint movements, demonstrating accurate and reliable data and the unique ability to provide force data throughout joint articulation. However, as the acquisition of RFD is at very small epochs (0-100 ms) at the initiation of a MVIC, the sampling rate of some isokinetic devices (~100 Hz) may be too low to provide meaningful information. In all devices, specific care should be taken to ensure the sampling rate is substantial enough. Interestingly, almost all research published on isokinetic testing does not report sampling rate in the methodology, which is a potential issue with respect to RFD. For this reason, the use of an appropriate load cell (sampling at, or around, 1000 Hz) is significantly better suited to manage this type of task, and should be the preferred methods for joint specific RFD data.

Protocol and Procedure

The procedure of collecting RFD is an extremely important consideration as small inconsistencies in methodologies can manifest as large deviations in data, and undermine the use of RFD in clinical practice. A common oversight when assessing force production is the material used by which the force is transmitted. Identical to the process by which a tendon transmits force from the MU, the tethering materials, both to and from the transducer, can produce notable variances in data if the compliance of the material is significantly altered. This can lead to changes in force velocity and joint fixation, and also lead to dissipation of force, therefore producing inaccurate information[1,63]. Physical medicine is often tasked with exploring variables in a population which is, or was, injured and or painful, which often leads to attempts to improve the comfort of the task, by adding cushioning or padding (Figure 6). The padding, albeit more comfortable to the individual, adds compliance to a testing system that requires rigidity for accuracy [149,209]. Folland et al.[149] demonstrated a potential range of motion deviation of 4 degrees when using a rigid tether dynamometer versus reported variance of greater than 15 degrees in standard commercial isokinetic devices which utilizes excess padding for patient comfort[209]. Excess compliance can be observed throughout any component of the system, from comfort driven designs of strapping and restraint, large padding on the dynamometric testing interface or the chair/table apparatus, or could potentially be the consequence of older machine components which allow unintended movement within the fixation. Not only does this change the tested joint angle, but it will also impact the angle of resistance, which should be perpendicular to the direction of the force produced. In the equation for torque ($T = F * r * \sin(\theta)$), where r = radius of the moment arm, F = force the angle,

and “sin(theta) represents the angle associated with the vector of force against the direction of resistance, the is equal to “1.0”. Any deviation from perpendicular (90 degrees to the force) will produce a = less than “1.0”, and represent a subsequent loss of efficient and accurate transfer of force. Therefore, it is imperative that the system be maintained as rigid as possible, whenever possible, and checked often.

Figure 6: The Humac Norm resistance pad

It is empirically most common, for the acquisition of RFD to be obtained for a single joint at the joint position associated with the highest force production, i.e., the position of optimal length-tension[1]. However, it is well documented that unintended changes in position will substantially vary the force production characteristics, leading to unreliability[1,61]. Murphy and Wilson documented statistically different RFD values produced within bench press exercise at elbow flexions of 120 degrees or 90 degrees, with 120 degrees producing a significantly greater RFD[61]. Furthermore, this study noted a low correlation coefficient between these joint positions[61], which was consistent with the findings of Bazyler et al. in 2015[210] during a static squat exercise at varying positions. Based on the findings from Bazyler et al.[210] and Murphy and Wilson[61], in conjunction with similar findings during knee extension testing, changes in approximately 30 degrees can produce substantial individual differences in RFD[72,115,211]. Therefore, intention and consistency in joint position is critical when investigating isometric force production. The testing position should correspond with the position of a specific

functional task, or with the position that relates to the maximal force capacity (determined typically by length tension relationships of the muscle-tendon unit).

The testing position should also be closely monitored for change throughout the session, as changes can be the result of compliance of the device setup or potentially the relative slack within the biomechanical system. Measurement, both prior to the contraction and during the contraction, is necessary as part of a standard methodology to ensure accurate data. With respect to position of RFD during multiple-joint tasks, such as a bench press isometric or a mid-thigh isometric pull, the large degrees of freedom associated with these comprehensive movements can be a concern. It is recommended that these movements utilize strict protocols overseen by trained professionals. This seems to both better remove comprehensive slack from the system, and better control the testing position.

Finally, the joint position selected for testing should reflect either the position of clinical relevance (as in an area of weakness or limitation), or the position most closely related to maximal force production of an associated movement task[61,63,212]. In most clinical testing protocols, this position is the peak length-tension and muscle fiber overlap, which is the location of the peak contraction capacity. This seems to limit the amount of variability, and is therefore empirically recommended for RFD and PF testing[1].

Pretension

The use of pretension during RFD acquisition is an important, but very convoluted, topic area[1,63,72,147]. Pretension describes the use of a relatively low percentage of maximal force, which the individual creates and sustains over a period of time, prior to the initiation of an explosive force contraction. The use of pretension offers value in the clinical set-up and procedural methodology avenues, along with removing slack, or compliance, in the testing system. Not only is it uncomfortable for some individuals to create maximal, rapid, force from a completely relaxed position, but this process allows, in some cases, for an unabated acceleration before making contact with the resistance strap or device. In some cases, the use of resting force (no pretension) is methodologically very difficult. As an example, the procedure for collecting RFD within a knee extension isometric contraction at 60 degrees of knee flexion would require a set-up which holds the shank in a position of 60 degrees, placing tension on the system to remove the slack, but not providing any additional force and able to be placed around the testing strap. In situations where the slack remains in the system, an artificial, spike in force once the limb contacts the strap can often be seen. Essentially, the individual is able to create rapid unresisted

force for a period of time. This creates a more concentric contraction prior to the isometric contraction and misrepresents the true isometric capabilities of the participant.

The use of pretension allows for improved consistence in repeated measurements, and joint angle accuracy. However, the use of pretension will make the identification of the 'onset of contraction' within the force trial, more difficult. The onset of the contraction marks the exact moment at which the individual begins to produce his/her testing contraction. This would be the moment by which any force time characteristics will be referenced, specifically time to peak force, time to peak RFD, or when reporting the RFD within specific epochs ($RFD_{0\text{-}50}$ ms, $RFD_{50\text{-}150}$ ms. When looking at exceptionally small time points for RFD and IMP, any variation in the detection of the onset of contraction can have substantial impact on results. Furthermore, the exact percentage of pretension force to be used in collection trials is not consistent across the literature.

Finally, the use of pretension will alter the force-time curve, both affecting the consistency and transferability of data, and also impacting the collected variables (such as impulse and RFD)[1,63,72,147]. Van Cutsem and Duchateau described a decrease in RFD (around 25%) associated with the use of pretension state[1,147]. Kamimura et al. also showed similar findings, a reduction in RFD, when the individual completed a countermovement immediately prior to an explosive contraction[213]. In regards to the amount of pretension, it seems there is an inverse relationship between amount of pretension and the effect on RFD[147,214].

At this time, recommendations for the exact percentage of MVC to be used for pretension are not known, rather it is suggested that small amounts of pretension force should be used over larger forces[80,88,98]. For these reasons, it is generally recommended that the capture of RFD include some pretension, which is consistently related to a percentage of MVC. Although the exact percentage is not known, it should be consistent, and large percentages should be avoided due to its impacts on RFD performance. If the procedure and setup are amenable to performance without pretension, the analysis of the data will be more consistent, assuming rigid testing procedures are followed[1,63,72,147].

Encouragement and Cueing

The concepts of encouragement and cueing, specifically the word choice and type of instruction provided to the subject both prior and during the trial, can have dramatic effect on subject performance[1]. During the trial, it is well documented that verbal encouragement impacts the performance of maximal force and RFD, therefore the recommendation is that verbal encouragement be implemented during all

trials of force production[215,216]. In regards to the specific type of instruction and cueing, two very specific phrases have been explored with maximal strength and RFD: 1- “Hard” or “Hard and Fast” 2- “Fast” or “Fast and Hard”[217-221]. Christ et al.[218] explored the impact of the terms “hard” versus “fast” on isometric RFD, identifying significantly higher RFD values (as much as 50%) when the subject was instructed to perform the trial “fast”, as opposed to performing “hard”. This study has been repeated (Bemben et al.[217], Sahaly et al.[219], Holtermann[221]) with similar results, and further reinforcing the use of the term “fast” in cases for which RFD is the priority. When maximal force is the objective of the trail, utilizing the term “hard” or “strong” has shown to have significant improvement of PF (20-46% increase)[219]. This, however, poses a bit of a clinical and methodological dilemma for synchronous testing of maximal force and RFD. It has been found that attempting to collect both variables will result in inconsistent values for both[1]. Therefore, the instruction should match the intended variable of interest, PF or RFD, and collecting both synchronously should be avoided when possible. However, as the exploration of RFD and its relationship with PF has evolved, RFD has been shown to have a positive relationship with maximal force[126], leading to a subsequent evolution in terminology. This intentionally instructs the individual to produce high force, but places the focus on the rapidity of doing so, while informing them of the relatively short period of time for the trial. The optimum terminology has, thus, become “fast and hard” with an emphasis on the subject of creating explosive force, but remembering to make as much force as possible, while removing any RFD trials with low peak force production (less than 70% of MVC)[72,149]. This should be explained to the subject, while also providing visual feedback with corresponding verbal analysis about their performance as to better encourage performance[72,149]. It is extremely helpful to both identify the relative brevity of the testing epoch and point out the simple comprehension metrics for RFD relating to the steepness of the curve. These instructions, along with proper cueing, and feedback can improve reliability and accuracy of RFD data[9,72,108]. Limited evidence has explored the use of either auditory or visual signals for the initiation of the contraction, as in a “3-2-1 countdown”, however the utility of such is unknown at this current time.

Familiarization

Along with instruction, it is necessary for each subject to complete a bout of familiarization trials, which may include a type of general warmup, prior to testing. A warm up should include a general movement strategy, force building tasks, and finally some type of neuromuscular activity which focus on moving quickly (such as quick feet tapping or jump rope). The familiarization trials should include at least 5 maximal, explosive, force production trials, with feedback regarding performance[1]. Depending on the individual’s activity and fitness history, the act of explosive force production may be foreign or uncomfortable. It is imperative, for the accuracy of the testing, that these psychological and physical

issues be mitigated prior to testing. Finally, with respect to rest and fatigue effects in testing, Noorkoiv et al.[222] demonstrated no fatigue effect in a large number of isometric contractions (3 second MVC's) when the individual was given 1 minute rest. As RFD requires very short epochs (~<500 ms), the fatigue effect can be managed with relatively short rest intervals (15-20 seconds) between trials[108,126].

Part VIII: Analytics and Data Interpretation of RFD and IMP

The final consideration, pertains to the area of data analytics and interpretation. Specifically, this area focuses on the selection of specific data variables, data filtering processes, and the process of trial window identification (Figure 7).

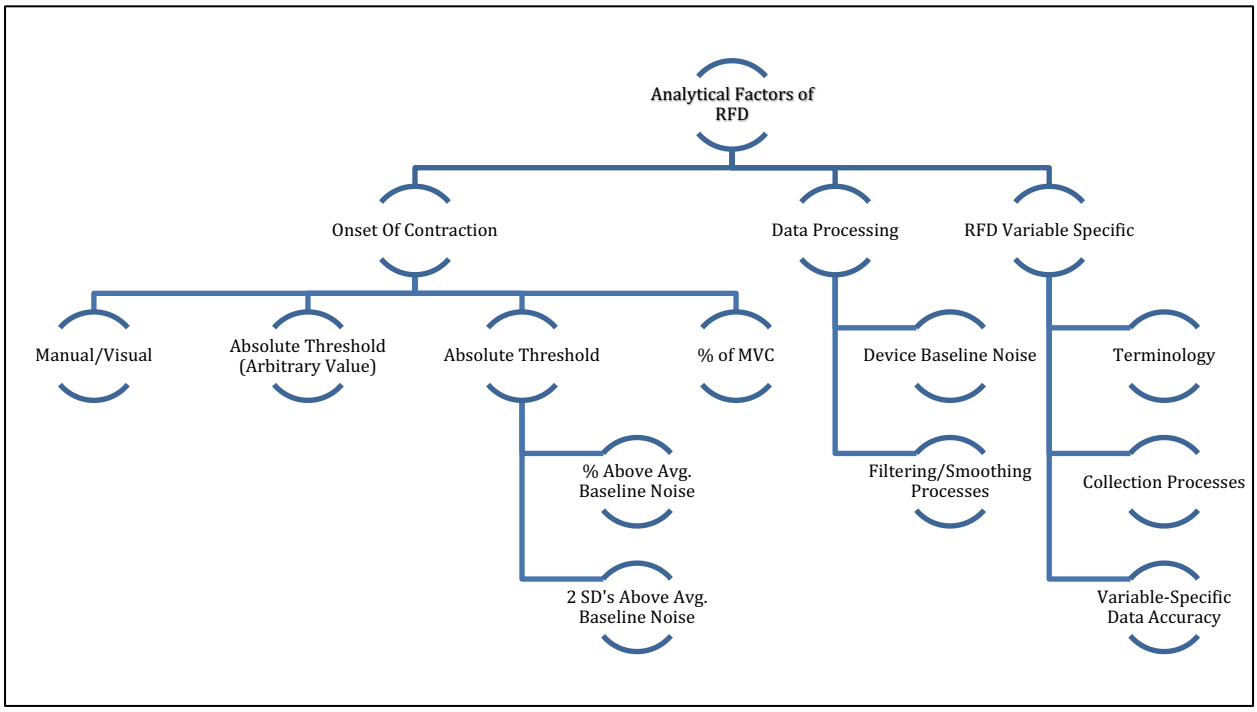

Figure 7: Analytical factors that may influence RFD

All force-time data is premised on a well-defined and procedurally consistent window of time. The ability to consistently identify the specific moment of force onset within a testing trial, has a cascading effect on the data analysis process. Inconsistency in the identification of the force onset point, or onset of contraction would subsequently change metrics such as time to peak force, time to peak RFD, and will also change the subset of data used in the calculation of impulse and RFD. However, the process of trial window identification proves very difficult, ultimately leading to disagreement in regards to best empirical practice[1,63]. While clinical advancements in set-up and methodology are attempting to remove the use of pretension states, specifically to enhance data analysis, there is limited empirical

recommendation at this time. Theoretically, should the tester know the baseline noise, the process of force onset would be the first observed force above the noise in any trial not utilizing pretension force. In practice, and in all pretension trials, the baseline noise in the system is not constant and thus this is typically not the research method of choice. A variety of force onset identification processes have been described in the literature. A series of publications, from 2002 through 2009[26,64,124,223], described and utilized an a automated process of detection, based on a change of force above a pre-set threshold, which could be an arbitrary, absolute (i.e. 5 Nm), or, a percentage of the force from the event, or based on a percentage of the individuals MVIC (i.e. 1.5% of MVIC)[224,225]. This MVIC is collected in a separate trail, which therefore necessitates the need for multiple contractions within testing. The absolute threshold is the most practically simple solution; however, it might offer limited transferability between certain cohorts and muscle groups, which have different force capacities. Therefore, the percentage, based on the force output within the same trial, threshold procedure would be a better inter-personal option, assuming the individual is able to compete a MVIC[1]. Assuming that most clinicians will have limited access to custom dynamometers, this presents a notable problem for clinical utility, being that the tester would need to be aware of the device and the baseline noise prior to selecting the threshold value. In many cases this would manifest as the tester arbitrarily selecting a value higher than necessary (i.e., 7-8 Nm). Considering that some individuals do not produce 5 Nm, or a relative 2.5% of MVIC, until roughly 25 ms of the force trial[1,226,227], the ability to measure the initial phases of RFD production (those from 0-50 ms) could be inaccurate[1]. An alternative to MVIC based percentages, but continuing to account for the device's baseline noise, would be defining the average baseline noise and setting the threshold at 2 standard deviations from baseline, or utilizing a percentage (i.e., 3% above baseline)[228] (Figure 8). Regardless of the method, inconsistent evidence and therefore limited recommendation exists on the best method in clinical and empirical research.

In 2010, Tillin et al.[108] proposed that the gold standard method is based on a manual / visual selection process as an alternative to the above automated methods. This process utilizes certain visual criteria in

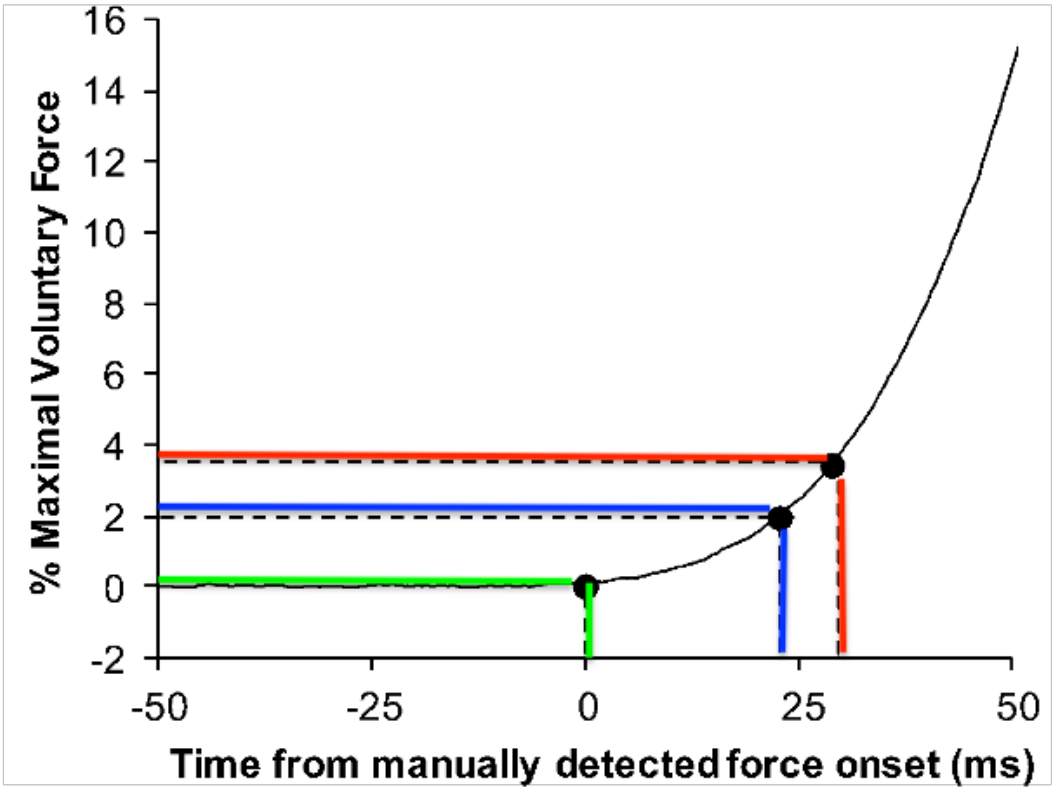

Figure 8: A representation of an unfiltered force/time curve depicting three different methods of "onset of contraction" process and how this can impact where the "0" time point may be. Lowest Dot/Green line = manual selection; Middle Dot/Blue line = 2% of MVC; Highest Dot/Red line = ~4% of MVC. Note the difference in time point of each method. Maffiuletti 2016,[1]

an attempt to better standardize the process, which included components of rejecting trials where baseline force was not consistent, standardizing the reference scale, and better defining the criteria of the force onset.[1,108,115,149]. Logistically, this method is much less efficient than any automated process, as it requires the tester or researcher to manually select this time point for each trial, but can produce reliable data (intra- and inter-rater standard deviation (SD) of 0.33 ms and 0.52 ms[1,149]). Citing work by Pain and Hibbs[229], Tillin et al.[108] highlighted the pattern recognition capabilities of visual inspection as the primary factor in the increased accuracy and onset of contraction. This presents an argument for manual processes over automated strategies; however, the visual process would need to adhere to the listed criteria, and the collection methodologies would also need to remain controlled. Part of this process, data smoothing/filtering, is commonly used to help improve the representation of the data output, and can be completed by a variety of processes, such as frequency filters[230]. While there is inherit benefit to smoothing data, specifically in cases of high noise, large amounts of smoothing/filtering will lead to more conformity which may remove small deviations from the data set.

These small deviations may represent real, although subtle, changes in the performance, which will be lost when filtered. Tillin et al.[231] highlighted this phenomenon that applying high smoothing/filtering processes to the data (especially data with high noise) may lead to inaccuracy of the manual/visual detection process, as the smoothing/filtering function could potentially remove too much data and therefore impact the force onset reference[231]. Therefore, minimal smoothing/filtering of the raw data is recommended (especially in the conditions of high baseline noise devices) and it appears that the "low amplitude, high frequency noise" will actually assist in the accurate identification of the contraction initiation[231].

Finally, there is also reported utilization of a percentage range method of force onset based on the peak force within the trial or based on the individual's MVIC. The initial report of this method was in 2008, by Dudley-Javorosk, et al.[232], the group establishing that by calculating the peak force of the trial first, kinetic variables can then be calculated for an epoch defined by the range of 20%-80% of the peak force. The publication supported this methodology by justifying that the lower threshold was used to eliminate the portion of the curve that is often the noisiest[232]. This also aided in the dilemma created by the difficult nature of automated force onset identification. With these metrics, Dudlley-Javorosk et al. found suitable acceptable between sessions reliability of RFD and PF testing[232]. A second publication reported similar findings, using the same 20-80% of PF, however this study found PF in a separate testing trial rather than using PF obtained within the same RFD assessment[233].

While each method has unique benefits and limitations, there is no overwhelming agreement on the process, although there is a general consensus that the procedure of visual/manual selection is best practice at this current time. However, consistent advances in automated processes are evolving, and are necessary to the success of RFD as a clinical tool, as the process of manual/visual detection is both impractical and problematic for the future automation of the process (in cases of software and client-facing testing apparatuses). The use of machine learning approaches are increasing in favour and interest; however, these methods require large amounts of data and analytic processes are not currently adequate. As machine learning methods improve, it is likely this will supersede the manual method. Regardless of the process selected, the concepts of the use of pretension, the device selected and its baseline noise, and the data smoothing/filtering should be discussed and considered.

The Selection of RFD Variables

The exact variable(s) chosen for research or clinical use are largely dependent on the quality of the data, the statistical accuracy associated with the specific variable, and the relative clinical value of the

variable. Once the force onset is established within a force-time trial, it is possible to then compute a series of RFD and IMP measurements. The most commonly described RFD and IMP metrics in both empirical and clinical practice are RFD/IMP taken at standard time intervals (i.e., RFD/IMP at 0-50 ms, 50-100 ms, and onward), or related to overlapping time intervals (i.e., RFD/IMP at 0-50 ms, 0-100 ms, and onward), although there is inconsistency in the time durations used (20 ms, 50 ms, 100 ms windows)[63,64,108]. In these cases, RFD/IMP is typically described by either the time interval ($RFD/IMP_{0\text{-}50}$ ms) or simply by the time point from "0" (RFD/IMP_{50} ms). Providing data in multiple intervals, or consecutive time points, RFD/IMP interval values can be used to provide more comprehensive analyses of performance and highlight areas of insufficiency[149], such as the interval at which the steepest RFD occurred during a trial, i.e., PRFD. It is important that the term PRFD be specified to mean instantaneous PRFD, or PRFD in the context of the peak of the set of intervals.

A series of publications[26,64,72,221,223] have also described and explored "relative" RFD/IMP, as an option to improve the robustness of the RFD/IMP profile. The concept of "relative" is referencing RFD/IMP with respect, or relative, to other stratification criteria, such as age, sex, certain time domains, or in relation to other kinetic data (such as peak force). An example of this would be RFD/IMP calculated over the time interval established from the contraction onset to one of a variety of force thresholds: a) time to the maximal force; b) time to any percentage of maximal force; c) time to any arbitrary force thresholds (i.e., 100 N, 200 N, or 500 N)[63,124,137]. Researchers have explored this collaboration, citing a positive association between absolute RFD and maximal force, therefore recommending some type of normalization strategy by which to manage this relationship[26,64,137,159,221]. By incorporating measures of relative RFD, more information about the time-specific aspects of the force curve could be helpful in identifying and exploring the physiologic components of RFD, independent of maximal force[63,193,221]. Furthermore, it would allow transferability and comparative analysis of data between muscles, muscle groups, ages, or activity scales[63,193,221]. However, relative RFD with respect to force production does have some notable setbacks. Sahaly et al., (2001) described the inaccuracy in relative RFD (normalized to maximal force) when the peak force was not the individual's true maximum[63,219], therefore presenting a problem both as a measurement of RFD performance as well as for repeated testing. The publication also pointed out that changes in maximal force, as in an improvement of maximal force capacity over a period of time, would therefore produce a relative RFD decrease, although the absolute RFD value remained constant. Furthermore, any changes in both maximal force and RFD (whether that be a decrease or increase) would mathematically leave relative RFD unchanged, although the performance of the individual would certainly be at a deficit compared to the prior testing. For this reason, it is

recommended that relative RFD, regardless of what it is being normalized against, be included with measures of absolute RFD for the same epoch and trial[63,219].

Reliability of RFD

A myriad of studies have explored the reliability and consistency of various RFD characteristics, collected on a variety of devices (Table 2). A publication by Hernández-Davó and Sabido (2014)[87] presented a table, which reviewed recent studies between 2004 and 2014 regarding the reliability of RFD, and noted that force plates and load cells were found to be the most commonly used and also the most reliable in terms of RFD testing. This is likely due to the large sampling rate and sensitivity of the devices and components. With reference to the isokinetic device, inconsistent evidence was found regarding its use for RFD[228]. This is likely related to some combination of the material compliance in the device (lack of rigidity due to comfort of the material), and the sampling rate (typically around 100 Hz in most units) utilized to explore the data. Isokinetic devices, such as the HUMAC NORM and Biodex units, have been shown to be reliable regarding maximal force[207,234], whether isometrically or isokinetic, as this variable requires less sensitivity and culminates over a much longer period of time (3-5 seconds) as compared to peak RFD (0-250 ms). In closing, the researchers concluded that RFD, especially in those instances of early epoch domains, can be very volatile, and that this volatility was likely the product of a myriad of subject and methodologic factors, not the device itself[87].

As described previously, a range of methods can be used to explore RFD in an isometric contraction. Many of these involve overlapping, confusing, and inconsistent nomenclature, which has undermined the quality and consistency of empirical evidence[88]. Of the available research, test-retest reliability of RFD has been shown to range from high to moderate throughout a spectrum of single joint (Buckthorpe et al. 2012 - knee extensors[62]; Mirkov et al. 2004 - elbow flexors[137]) and multi joint (Tillin et al. 2010 - static squat[9]; Haff et al. 2015 - isometric mid-thigh pull[88]) trials. Regardless of the process used to calculate RFD, it has been shown to be generally less reliable than that of maximal force (which has a reported coefficient of variance (CV) of around 2-4%[9,108]) , which is unsurprising based on the sensitivity of the RFD metric[9,108]. However, the exact understanding around the impacts of contraction type, the torque-angle-velocity relationship (described by King et al. 2006[235]), and the use of dynamic RFD in function are not fully known. Considering that RFD plays a large role in power and functional tasks, the acquisition of RFD within dynamic movements is potentially valuable.

Prior to Haff et al. (2015)[88], minimal investigation had occurred to specifically explore and compare various methods of RFD. In this paper they explored the reliability of a variety of PF and RFD metrics

collected during two, five-second, isometric mid-thigh pulls trials using a load cell apparatus. These researchers quantified PF and RFD within the same trial (using instructions for “hard and fast”). The researchers included values of absolute force: 1) maximal force created within the 5-second tested window; 2- force at 30, 50, 90, 100, 150, 200, and 250 ms) and various methods of RFD (1-RFD_{xx} at 0–30, 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 ms; 2) PRFD documented as the largest RFD collected when the trial was

Table 2: Summary of studies analyzing the reliability of RFD measures (Adapted and Updated from Hernández-Davó and Sabido (2014)[87]

Study	Task	Device	Variables Assessed	Reliability (ICC)
Chiu et al. 2004[236]	Dynamic: CMJ	FP & LPT	PRFD, TTPRFD, AvgRFD	FP: 0.91.0.95 (PRFD), 0.16-0.58 (TTPRFD), 0.96 - 0.98 (AvgRFD); LPT: 0.89-0.94 (PRFD), -0.03-0.72 (TTPRFD), 0.92-0.97 (AvgRFD)
Chiu et al. 2004[236]	Dynamic: SJ	FP & LPT	PRFD, TTPRFD, AvgRFD	FP: 0.88.0.93 (PRFD), 0.91-0.97 (TTPRFD), 0.9 -0.95 (AvgRFD); LPT: 0.8-0.93 (PRFD), 0.81-0.93 (TTPRFD), 0.7-0.93 (AvgRFD)
Kawamori et al. 2005[66]	Dynamic: SJ	FP	PRFD, TTPRFD	0.95 (PRFD), 0.98 (TTPRFD)
McGuigan et al. 2006[113]	IsoM MTP	FP	PRFD	> 0.96
Holtermann et al. 2007[2216]	IsoM LE	LC	RFD 0-300ms	0.88
Maffiuletti et al. 2007[202]	IsoM & IsoK LE & LF	IsoK Dyn	IsoM-PRFD IsoK-PRFD	LE: 0.87-0.92 (IsoM-PRFD), 0.97-0.99 (IsoK-PRFD); LF: 0.9-0.91 (IsoM-PRFD), 0.97-0.99 (IsoK-PRFD)
McGuigan et al. 2008[1147]	IsoM MTP	FP	PRFD	> 0.96
Gonzales-Badillo et al. 2009[237]	Dynamic: CMJ	LPT	PRFD, RFD at PF	0.88-0.97 (PRFD), 0.87-0.96 (RFD at PF)
Ingebrigtsen at al. 2009[238]	IsoM Biceps Curl	Isokinetic dynamometer	PRFD	0.69
Kraska et al. 2009[109]	IsoM MTP	FP	PRFD	0.86
Stevenson et al. 2010[239]	Dynamic: CMJ	FP	Ecc PRFD; Con PRFD	0.8-0.84 (EccPRFD); 0.78-0.83 (ConRFD)
Tillin et al. 2010[108]	IsoM: LE	LC	RFD 0-50ms, 50-100ms, 100-150ms	Coefficient of Variation: 12.8 (0-50ms); 5.7 (50-100ms); 12.5(100-150ms)
Comfort et al. 2011[240]	Dynamic: PC, HPC, MTPC, MTCP	FP	PRFD	0.92 (PC); 0.95 (HPC); 0.93 (MTPC); 0.96 (MTCP)
McLellan et al. 2011[142]	Dynamic: CMJ	FP	PRFD, AvgRFD	0.89 (PRFD); 0.89 (AvgRFD)
West et al. 2011[110]	IsoM MTP	FP	PRFD	0.89
Leary et al. 2012[144]	IsoM MTP	FP	PRFD	> 0.81
Muehlbauer et al 2013[111]	IsoM: PF	Isokinetic dynamometer	PRFD	0.93
Marques et al. 2014[241]	Dynamic: CMJ	LPT	PRFD, TTPRFD	0.91 (PRFD); 0.8 (TTPRFD)
Marques et al. 2014[241]	Dynamic: CMJ	LPT	PRFD, RFD at PF	0.98 (PRFD); 0.93 (RFD at PF)

Prieske et al. 2014[56]	IsoM: Biceps Curl	Isokinetic dynamometer	PRFD, RFD at 30ms, 50ms, 100ms, 200ms, 300ms, 400ms	0.68 (PRFD); 0.76 (30ms), 0.8 (50ms), 0.85 (100ms), 0.95 (200ms), 0.96 (300ms), 0.97 (400ms)
Haff et al. 2015[88]	IsoM MTP	FP	AvgRFD; PRFD at 30sm, 50ms, 100ms, 150ms, 200ms, 250ms	AvgRFD = 0.74 ; All PRFD time bands = 0.95
Comfort et al. 2015[242]	IsoM MTP	FP	AvgRFD at 100ms, 200ms, 300ms at various knee/hip positions	Within Session: (120° knee+ 125° hip)=.908, (130° knee+ 125° hip)=0.909, (140° knee+ 125° hip)=0.883, (150° knee+ 125° hip)=0.898, (120° knee+ 145°hip)=0.922, (130° knee+ 145°hip)=0.896, (140° knee+ 145° hip)=0.849, (150° knee+ 145° hip)= 0.877; Inter Session: (120° knee+ 125° hip)=0.978, (130° knee+ 125° hip)=0.942, (140° knee+ 125° hip)=0.930, (150° knee+ 125° hip)=0.948, (120° knee+ 145° hip)=0.983, (130° knee+ 145° hip)= 0.976, (140° knee+ 145° hip)= 0.803, (150° knee+ 145° hip)=0.948
Zaras et al. 2016[243]	IsoM Leg Press	FP	RFD at 50ms, 100ms, 150ms, 200ms, 250ms	0.93 (95% CI: lower = 0.85, upper = 0.98)
Sayers and Bishop 2017[244]	Supine Med Ball Throw	9-camera 500 Hz infrared motion capture system (Qualisy)	PRFD for ball throws weighing 5% and 10% of their 5RM bench press	PRFD: 0.83 (10%); 0.85 (5%)
Hornsby et al. 2017[245]	IsoM MTP	FP	IPRFD	IPRFD (ICC = 0.93)
Desmyttere et al. 2019[246]	IsoM Hip Assessments	*Groin Bar Device	PRFD and AvgRFD determined and used by scanning successive 200ms windows with multiple hip movements	PRFD: ADD=0.81 (0.65-0.90), ABD=0.68 (0.42-0.83), ER=0.80 (0.65-0.89), IR=0.84 (0.71-0.91), EXT=0.61 (0.36- 0.77), FLX= 0.72 (0.53-0.84); AvgRFD: ADD=0.92 (0.85-0.96), ABD=0.84 (0.67-0.92), ER=0.91 (0.83-0.95), IR=0.91 (0.84-0.95), EXT=0.81 (0.63-0.90), FLX=0.90 (0.81-0.95)
(CMJ-Counter Movement Jump; FP-Force Plate; LPT-Linear Position Transducer; RFD-Rate of Force Development; PRFD-Peak Rate of Force Development; TTPRFD-Time to Peak Rate of Force Development; AvgRFD-Average Rate of Force Development; SJ-Squat Jumps; MTP-MidThigh Pull; IsoM-Isometric; IsoK-Isokinetic; LE-Leg Extension; LF-Leg Flexion; PF-Peak Force; PC-Power Clean; HPC-Hand Power Clean; MTPC-MidThigh Power Clean; MTCP-MidThigh Clean Pull; PF-Plantar Flexion; Ecc-Eccentric; Con-Concentric; ms-milliseconds); ADD-Adduction; ABD -Abduction; ER-External Rotation; IR-Internal Rotation; Ext-Extension; Flx-Flexion				

divided into 2 ms, 5 ms, 10 ms, 20 ms, 30 ms, and 50 ms window intervals for the trials; 3-ARFD or index of explosiveness, as described by Zatsiorsky[89], and defined as RFD in the time from onset of contraction to the PF; 4) starting strength (RFD within the time window created by the Force onset to

0.5 PF) and acceleration strength (RFD within the time window created by 0.5 PF to 1.0 PF), also as described by Zatsiorsky[89]. In concurrence with Hernández-Davó and Sabido (2014)[87], Haff et al. 2015[88] highlighted that the exact method used when exploring RFD has substantial impact on the reliability of the data. With respect to the force data, all variables had acceptable reliability, with the highest reliability being with PF (CV =1.7%; confidence interval (CI) = 1.2-2.9%; intraclass correlation alpha (ICCa) = 0.99)[88]. This is consistent with previously established research[28,104,113,114,116,143,247], highlighting PF as an extremely reliable measure. However, in reference to RFD, the reliability was not found to be as consistent, and in some cases, poor. The use of RFD_{xx}, at a set of predetermined epochs (i.e., 0–30, 0–50, 0–90, 0–100, 0–150, 0–200, and 0–250 ms) was found to exhibit acceptable intrasession reliability, however the RFD_{xx} reliability of very early epochs (0-20 ms, 0-50 ms) may be of concern[248]. Likely due to concerns with force onset identification and the intricacies of the neural involvement within this time domain, Buckthorpe et al. 2012[9], Tillin et al. 2011[249], and Jenkins et al. 2014[24] have demonstrated significantly higher CV, in the initial/early phase, 0-50 ms window (12.8–16.6 % (0–50 ms); 4.5–5.3 % (0–100 ms); 4.5–5.1 % (0–150 ms). Furthermore, regarding RFD_{xx}, according to Maffiuletti et al. 2016[1] and Buckthorpe et al. 2012[9], the epoch 50-100 ms has been found to be the most reliable epoch, compared to 0-50 ms and 100-150 ms, due to the probability that the sharpest RFD is generally within this time window. While Haff et al. 2015[88] did not report specifically on IMP, IMP has been shown to have similar reliability to that of RFD when compared over similar time periods[1].

Acceptable reliability was not found to be true in the case of ARFD (ICCa = 0.74, 90% CI = 0.32–0.92), or with starting and acceleration strength, likely due to the variability in the time needed to produce peak force and the variability in the amount of force generated within standard epochs[88]. Similarly, the reliability of PRFD also was found to have unacceptable levels of reliability for all values (instantaneous and interval based PRFD), except PRFD at 0-20 ms, which was just above acceptable values (ICCa = 0.90, 90% CI = 0.73–0.97; CV = 12.9%)[88]. Therefore, based on these findings, it is recommended that RFD be explored in predetermined time intervals, PRFD be determined for 20 ms intervals, and that each variable be explained adequately to represent the methodology by which the variable was acquired. Specific epochs should be used when there is interest in a given time domain, such as the time associated with a functional task or movement.

Summary of RFD Characteristics and Methodologies

It is clear that RFD can be influenced by a variety of factors (i.e., measurement devices, types of muscle contraction, methods and instruction, analysis and variable selection,[63,88]). In addition to these factors, the notable variability found within subjects and throughout individuals[149], and the inconsistencies in

terminology and nomenclature further complicate its methodological accuracy and utility. Ultimately, this manifests as the inability to repeat testing methodologies and difficulty in the generalization of the data, essentially increasingly the difficulty of reporting and empirically exploring RFD throughout activities, populations, and groups[63,88,250]. With this in mind, steps can be taken to help improve the accuracy of data, and ultimately should be an utmost priority.

This begins with the use of terminology around both the methodology of collection and the intricacy of analysis. One of the most apparent undermining principles to RFD reliability is the inconsistent use of the terms around its operational definition and the exploration of the variables within it. However, as further sub-divisions and more intricate versions of RFD/IMP are utilized, nomenclature becomes an increasing problem, especially in cases of transferability and cross-analyses. It is important that RFD/IMP be described for the time interval calculated and not simply by the term RFD or IMP. While this is seemingly apparent, reporting errors, or omissions, are common problems when utilizing RFD/IMP, especially in clinical practice. As outlined by Maffiuletti et al.[1], there are general principles which can help govern this evolving landscape and should serve as a checklist for collection of explosive force. This includes the device/system rigidity (or low compliance), the capability of sampling above 500 Hz, and the specific position and type of contraction for which RFD/IMP are acquired should also be considered.

In terms of analysis, limited filtering should be used when possible as this appears to impact the reliability of the data, especially in terms of identification of force onset in the early phase. The process of determining “onset of contraction” seems to be a consistently reported area of concern, by which many studies have proposed remedies, but no agreed solution has emerged. There is also the use of pretension for RFD, and its impacts on performance and on analysis. Avoiding pretension will improve the accuracy of the onset of contraction, although it may be uncomfortable for the individual in some cases. It is recommended that a pretension state be used, or a methodology be put in place to remove the compliance entirely for the testing position without pretension.

RFD and PF are unique, and exclusive measurements. While the capacity to create explosive force does depend on maximal force characteristics, especially in the later phases (>250 ms) of explosive force profiles, these two metrics should be obtained in exclusive trials. For reasons of cueing and instruction, along with the sample duration, it has been shown to be unreliable to acquire both RFD and PF within the same trial. RFD, and explosive force, should be encouraged using the instruction, “fast”, as opposed to PF which typically responds better to the term, “hard”. Regardless of the type of trial, familiarization of the

task should be completed and the individual be given feedback, auditory and visually, for their performance. Focus should be placed on the representation of the force-time curve, noting the steepness of the curve and verbally accommodating to the initiation of the pretension state. Inter, and intra, individual variability within RFD testing is common, therefore testing should include multiple trials and the average taken for the variable over those 3-5 trials. Trials with notable baseline noise, or a substantial countermovement, should be removed and discussed with the individual. Very short, ~1 second, contractions are sufficient for RFD collection (assuming the intention is explosive, early phase force), and will therefore need relatively short periods of rest (approximately 20 seconds) between testing trials. With this process, no fatigue effect has been shown, even in studies with large numbers of trials[126]. While the lack of IMP related research and evidence is apparent throughout the above sections, RFD plays a major role in the production of IMP and therefore should be considered when collecting RFD using the listed information and criteria.

Finally, it is recommended that maximal force be collected in a separate trial from RFD, and that RFD/IMP be described in relation, or relative, to maximal force if the intention is to cross reference this data or provide normative values, and normalized to body weight, age, sex to account for any confounding effects. IMP, as with RFD, should be explored within a variety of specific time epochs that are valuable or representative of tasks, movements, and goals.

Part IX: Rationale for Current Research

The value of RFD has been well established, referenced, and justified throughout this literature review, while the relative information on IMP is lacking. Appreciating that RFD, along with PF, are responsible for IMP, it can be reasoned that IMP is also very valuable, although this concept needs to be further empirically investigated. RFD has been shown to be a better representation of rapid force capability than maximal force, especially in the context of athletic performance and certain ADL tasks, such as balance. While there are certainly some limiting factors to RFD/IMP, it is undeniable that RFD/IMP plays a vital role in performance, injury profiling, and rehabilitation[1,98-107]. Therefore, it is of significant value that professionals and clinicians measure, examine, and intervene in cases of RFD/IMP impairment. RFD/IMP as measures of force capability, have the ability to become a major role player in various aspects of assessment. The obvious avenue is pre- and post- injury testing algorithms; utilizing RFD/IMP to profile athletes, clients, and patients specifically related to joints, tissue, or movements. This will potentially be used as a supplement to the current testing protocols by which professionals can more specifically analyse the nervous system and explosiveness of a given task or movement; possibly in performance as a ‘readiness’ tool, the profiling of a player to determine how the individual is physically, mentally,

neurologically, poised for training, sport, or performance. The capability is certainly expansive, and as the evolution of research continues to explore further, it is likely RFD/IMP will become play a more important diagnostic role for clinicians.

Currently, RFD/IMP is relatively unused within the rehabilitation and performance community, despite the current information that many rehabilitation processes fail to restore normalcy in the involved limb[1,2,14,15]. This is a combination of two variables: 1) access to testing devices; and, 2) education about RFD, which includes basic understandings of human biomechanics, kinesiology, and physics. The collection of RFD requires the use of equipment, both hardware and software, by which force is analyzed in very small epochs, a task that is impossible without high sample rate software/hardware. While the use of isokinetic devices for testing purposes has been shown to be very reliable[205,207,234], these machines are also extremely immobile, being bulky, heavy, and generally affixed to a location. From a testing perspective, clients, patients, or athletes would need to travel to these locations for any testing purposes, which adds time and monetary costs. As it currently relates to clinical practice in physical medicine, the most commonly described assessments of force are manual muscle testing (MMT) and hand-held dynamometry (HHD). MMT, using a manual resistance to obtain and subjective force output, is extremely practical, but highly questionable in terms of reliability and validity[619]. An improved option, in terms of quality of data collection, the HHD is also a very practical, and cost-effective device, and has much higher reliability and thus better clinical utility[19,251]. However, if RFD/IMP is of interest, HHD technology is typically limited to reporting data in terms of PF only. In addition, hand held dynamometers have been shown to under-report values when compared to isokinetic testing devices[251]. The use of RFD/IMP is uncommon due to the barriers described above, therefore it is of clinical value to have access to a more suitable option. The load cell is a device that can measure deformation (compression or tension) that, when compared to the HHD, is equally as portable and practical, yet slightly more expensive. However, the load cell can report a spectrum of data, including FTD and average force, which is substantially more robust and objective than the HHD or MMT. This data is obtained during isometric contractions, and thus less descriptive than isokinetic or force plate units, but the load cell is markedly less expensive and more portable than these devices.

Limited data exists with respect to reliability and normative data, specifically kinetic variables, such as RFD, when using a load cell. This research intended to explore the use of a load cell as a clinically practical alternative to an isokinetic testing device in investigating kinetic variables, specifically characteristics of explosive force (RFD). The primary aim of this study was to describe, and compare, the inter- and intrasession reliabilities of load cell technology kinetic variables collected via an isometric knee

extension contraction in healthy individuals using two, distinct protocols: 1) constrained position with rigid fixation; and, 2) unconstrained position with no fixation on a physiotherapy plinth. A secondary aim was to compare the variance of those same kinetic variables against kinetic data collected on a gold standard isokinetic device. The outcomes of this research could be useful to identify the accuracy of field testing or clinical testing protocols, help future researchers and clinicians establish clinical normative data sets, aid in the assessment of rehabilitation progression, and potentially play a substantial role in determining readiness and risk assessment in knee conditions.

CHAPTER THREE - STUDY 1

Intrasession reliability of kinetic variables collected during an isometric knee extension using novel load-cell technology in healthy individuals

Prelude

It was established in the literature review, that rate of force development (RFD) and impulse (IMP) though important mechanical measures of muscular performance are relatively unused within the rehabilitation and performance community. This is a combination of two variables: 1) access to testing devices due to cost; and, 2) education about RFD, which includes basic understandings of human biomechanics, kinesiology, and physics. A portable low-cost load cell device may address the first issue and in turn over time the second issue can be resolved with continual use of such devices. However, limited data exists with respect to reliability and normative data, of kinetic variables, such as RFD and IMP as collected using a portable load cell device. Therefore, the primary aim of this study was to describe, and compare, the intra-session reliability of load cell technology kinetic variables collected via an isometric knee extension contraction in healthy individuals using two, distinct protocols: 1) constrained position with rigid fixation; and, 2) unconstrained position with no fixation on a physiotherapy plinth.

Introduction

As the innovation and evolution of medical management related to various orthopaedic injuries continues to progress, the concept of reintegration and readiness have garnered increasing attention in an attempt to diminish the risk of reinjury, and better profile a person's relative capacity for a given task, skill, activity, or sport[1-7]. While readiness and reintegration are popular terms used in the athletic population, these concepts are equally as useful and important in the general population, when considering tasks such as the ability to recover balance during an unanticipated perturbation[9,10,32]. Regardless of the population, a subject's performance profile should include a comprehensive battery of local and specific measures, such as muscular endurance or peak force production, as well as standardized functional movement tests, such as hop testing or single leg balance assessments[1-7]. These assessments typically include isolated tissue or joint performance objectified by a single maximal capacity of a contraction (peak force - PF) or the volume of repetitions completed at a given weight (muscular endurance). These data have demonstrated empirical value in evaluating a range of cohorts, from age-related strength changes in the lower extremity[11,13-17,120] to limb symmetry knee extension strength after anterior cruciate ligament reconstruction[14-16].

There is an emerging interest in investigating force-time characteristics as they are more closely correlated with tissue capacity and may provide better information about force production. In particular, RFD and IMP, which denotes force is produced as a function of time, is gaining clinical popularity. Measures of RFD and IMP have been shown to provide a more defined insight into neuromuscular characteristics, such as muscle-tendon unit (MTU) stiffness[17,18] , MTU physiology[10,19], nervous system capacity[20-22], and psychologic confidence[1,23-26]. Moreover, increases in rapid force production have been associated with improvements in performance in numerous tasks such as sprint speed and weightlifting[27,28], along with activities of daily living, such as increases in walking speed or sit to stand actions[29-31]. Thus, RFD and IMP measurements may be more valuable both when describing risk and readiness post-injury, such as after anterior cruciate reconstruction[22], and when optimizing performance[88,104,116,252].

Currently, RFD and IMP are relatively unused within rehabilitation and sports performance settings, primarily due to access to testing devices. The collection of RFD and IMP requires specialized equipment using particular hardware and software analyse force in small-scale epochs. Devices such as force plates and isokinetic devices are useful in collecting RFD and IMP, but have traditionally been available only in hospitals, research labs and human performance centers at a cost that is unfeasible for most clinicians. A more practical and cost-efficient approach to measuring force-time measures would be a load cell. Moreover, if this device is accurate in clinical testing scenarios of kinetic data, such as on a physiotherapy

plinth, it would further support its use in clinical environments. While a plethora of studies have examined the reliability of commercial isokinetic dynamometers[67,68,71] limited data exists concerning the reliability of knee extension RFD and IMP using a portable load cell. Therefore, the primary aim of this study was to describe and compare the intrasession reliability of a portable load cell used in an isometric knee extension in two distinct layouts: 1) a constrained position with the rigid fixation of a dynamometer; and 2) an unconstrained position with no fixation on a physiotherapy plinth.

Methods

Participants

Thirty-two volunteers (14 males and 18 females: age: 31.8 ± 7.91 yr., height: 170 ± 9.13 cm, body mass: 77.1 ± 23.9 kg) participated, and reported their right limb as dominant (defined as the leg they would use to kick a ball). All individuals were deemed healthy according to their PAR-Q questionnaire, with no current health conditions that would limit strenuous exercise. Individuals were excluded if they had any prior surgical intervention that would limit maximal knee extension performance. All participants had the benefits and risks of the investigation explained to them verbally and in written form, and signed an informed consent before participation. The participants were informed that participation was voluntary and could withdraw at any time. Ethics approval for this study was obtained from the Auckland University of Technology Ethics Committee (19/447). Before testing all participants gave written informed consent.

Study Design

A cross-sectional, repeated measures design was used for comparative analysis of reliability for PF, RFD and IMP metrics during a maximal voluntary isometric contraction (MVIC) knee extension with a load cell device in rigid and non-ridged protocols. All participants attended a single testing session which consisted of three sequential rapid MVICs across three protocols. All data were collected by one researcher to reduce variability.

The Load Cell Device

The Load Cell device was a wireless force measurement system comprising of a load cell device with wireless telemetry, and an intuitive software package (SPRINZ Laboratories, Auckland University of Technology).

Procedures

Data was collected using 3 ‘protocols’. These protocols involved varying degrees of knee flexion angle and constraint, or rigidity, designed to compare laboratory and clinical environments. Protocol 1 was

defined as the Load Cell + Constrained + 90 degrees (see Figure 9.a). The participant was seated upright in the chair of the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY) at a hip angle of 85º, with shoulder, waist, and thigh straps affixed to reduce body movement during contractions. The load cell was tethered to the isokinetic dynamometer and the individual's lower leg ~two cm superior to the lateral malleolus using a steel chain. The knee was measured and maintained at 90º, throughout the set-up and trials, by shortening or lengthening the chain. The chair was adjusted to maintain both the center of rotation just beyond the edge of the chair and that the line of force production was maintained in-line with the orientation of the load cell. The 60º knee flexion position, as seen and tested in protocol-2 (description below), was not collected due to the inadequacy of appropriate angular fixation. There was no suitable fixation for the load cell by which the resistance to the force production was perpendicular to the attachment point on the shank, therefore only the 90º position was collected. The participant was instructed to place their non-testing limb behind the counterforce pad and hold the handles on both sides of the chair to further reduce instability. The computer, with software visible, was placed directly in front of the participant to be used for practice trials, feedback, and the pretension threshold. The pretension mark for this device and protocol was 120 Newtons (N), while the collection threshold was 160 N (i.e., the trial initiation was established once the force produced was >160 N).

Figure 9: Images of protocols 1 and 2. 9.a = protocol 1 (Constrained): Isokinetic dynamometer chair + Load Cell Device + 90 degree knee position; 9.b = protocol 2 (Unconstrained): Load Cell + Plinth + 60 degree knee position

Protocol 2 (Figure 9.b) and 3 (Not shown) both involved the use of a physiotherapy plinth, rather than the use of the isokinetic dynamometer chair, which was identified as “unconstrained”. Protocol 2 utilized the Load Cell + Unconstrained + 60 degree knee position while protocol 3 utilized the same Load Cell + Unconstrained set up but at 90 degrees. For both protocol 2 and 3, the participant was seated on the edge of a clinical plinth (table), and allowed to self-select a position while meeting the following criteria: 1) the participant must maintain this position throughout the trials; 2) the participant must hold the sides of the table; and, 3) the participant must shift towards the side of the table being tested so that the line of force must align to the fixation point which was previously located. Once seated and comfortable, the participant was sat on the edge of the plinth two cm superior to the lateral malleolus using a low compliance, steel chain, and a towel was placed under the distal thigh between the thigh and table. The plinth had a very rigid, uncomfortable, surface edge which was found to be problematic in pilot testing. The participant was asked to create a submaximal force (to achieve the true testing position and remove any slack in the chain) and the knee was measured to either 60º (protocol 2) or 90º (protocol 3) respectively, according to the intended position. Every participant completed both knee joint angles positions; however, the order was varied from session to session and from participant to participant. Note: the chain to table fixation was different for the two knee positions to accommodate for this. Throughout practice trials, the participant was allowed to move and change position, however, once the testing began, no further changes were allowed, and the participant’s position was recorded for future testing sessions. As with protocol 1, the computer monitor was placed within view of the participant for purposes of practice trials, pretension, and feedback. The pretension mark for this device and protocol was 120 N, while the collection threshold was 160 N.

Each participant warmed up by cycling at low to moderate resistance using a self-selected pace for three to five minutes. They were then placed in the constrained protocol for familiarization. Familiarization occurred at every session using the constrained protocol, regardless of the randomized testing order, and included a series of progressive, ascending force output isometric knee extension trials, which culminated with at least one trial at maximal effort. The participant was given verbal and visual feedback during these trials regarding performance and education was implemented in cases of confusion or to troubleshoot positioning. After familiarization trials were completed, the participant was asked to dismount the chair, and a five-minute rest commenced before the initiation of data collection. As part of the familiarization and practice trials, specific instruction and verbal cueing were explained and used. The term ‘fast’ in “fast and hard” was consistently emphasized throughout all testing occasions, which is necessary when collecting RFD and IMP metrics as opposed to maximal force[156]. The participant was given strong verbal encouragement throughout each trial.

After the familiarization trials and five-minute rest, the participant was then placed on the randomly allocated protocol and knee position. The participant was allowed up to five practice trials including verbal and visual feedback, and the participant was encouraged to complete at least one maximal effort contraction before finishing the practice trials. For testing trials, the participant was told to achieve the determined pretension state and hold at this level for two seconds by slowly extending the knee into the strap and visualizing the force line on the monitor. Once the force curve was steady at the pretension threshold, the primary investigator (PI) would begin a count down from 3 ("3-2-1-Go-Go-Go-Go-Go-Stop"). The participant was instructed to begin the MVIC at any point after "1" and maintain the contraction until told to "stop".

Each participant completed three testing trials at each protocol. Due to the small testing domain, the rest between repetitions was set at 10 to 30 seconds based on participant preference as described by previous researchers [222]. The force-time curve was visually inspected for large deviations in force production (>250 N from prior trials), or notable countermovement, or inconsistencies in the pretension state. If evident, these false contractions were removed, and the trial repeated. The testing order was dictated by random order assignments for each participant.

Data Processing

Force data was collected at 1000 Hz using the Load Cell device. Raw unfiltered force-time data was exported for subsequent analysis in CSV format. Only right leg (dominant leg) data was utilized for analysis. The data was then imported and analyzed in MATLAB (MathWorks, Natick, MA), using a custom algorithm. Each trial was trimmed to length to include a pretension period of at least 0.5 seconds, force onset, isometric contraction for at least one second, and a force offset. The onset of force was defined as an increase in force that was greater than three standard deviations (3 SD) of force calculated from the 350 ms pretension window within 1 second before the contraction[1,71,72,253]. A modified version of this method was used; where the onset of force was calculated as the first 3 SD threshold crossing from the location of peak force working backwards. Outputs were visually assessed for methodological outliers, which were removed from the analysis. Peak force (PF) was determined as the absolute maximum force recorded during the entirety of the two-second contraction; and 20% and 80% of this peak force were calculated. All further variables of interest were then determined from within the time interval created by the 20%-80% peak force thresholds ($time_{2080}$), as described by Cobian et al. (2017) and Dudley-Javoroski et al. (2008)[232,233] (Figure 10). Rate of force development (RFD_{2080}) was the average slope over the epoch (F/t) and impulse (IMP_{2080}) was the area under the force-time curve, during $time_{2080}$.

Peak rate of force development (PRFD) was calculated using a 10 Hz 4th order low-pass butterworth filter.

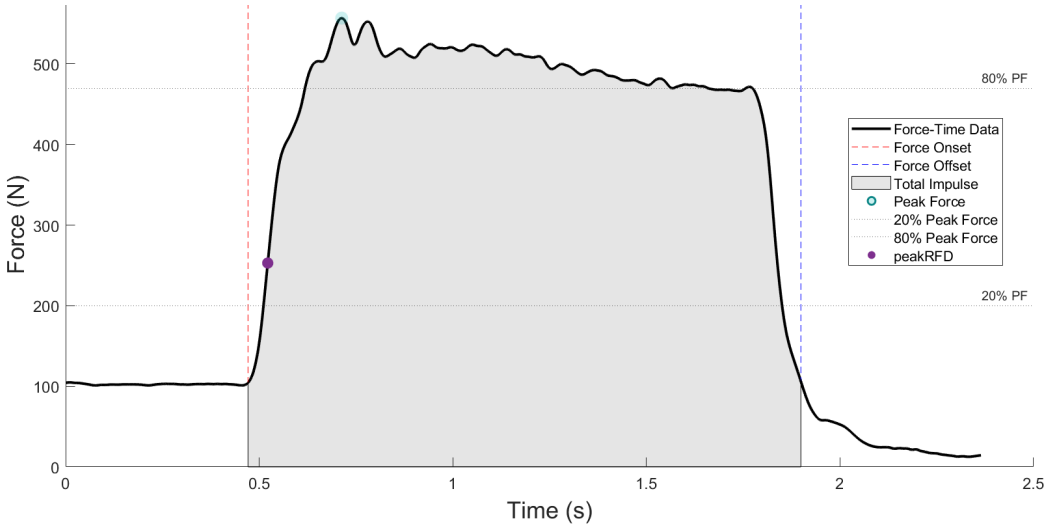

Figure 10: Visual representation of the force-time data for the load cell. This figure outlines the onset of contraction methodology used (reverse 3 SD method). Note: The large arrow describes the direction by which the application of the 3 SD pretension window threshold was applied. The blue dot highlights the peak force in the trial

Statistical Analysis

All statistical analysis was conducted using RStudio IDE (Version 1.4.869, 2009 – 2020 RStudio, PBS). The statistical analysis explored the intrasession reliability for each protocol. Each subject completed a series of at least 3 trials at each protocol. If less than 3 trials were conducted, the subject was removed from any further analysis. Outlier analysis was conducted using intrasession, intra-subject z-scores. Boxplots were used to visually check for outliers of the calculated z-scores (rstatix version: 0.6.0). Only extreme outliers were removed from the analysis. Normality of each intrasession variable was confirmed using Shapiro Wilks test. Mean and standard deviations were calculated. No significant inter-limb differences were observed and so the analysis is of the right limb only. There was no gender bias found, thus genders were combined for all analysis. The within-subject coefficient of variation (CV), and intra-class correlation coefficient (ICC) (two-way mixed effects, absolute agreement, type = single) were used to explore systematic change, absolute and relative consistency respectively. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability when either the ICC > 0.67 or the CV < 10%, but not both, and small variability when ICC > 0.67 and CV < 10%[254,255].

Results

For all variables, protocol 2 (Unconstrained + 60 deg) demonstrated the lowest ICC, and largest CV%, values when compared to the other two protocols. PF was found to have "very high" ICC inferences across all protocols (CV = 3.20%-4.50%) (Table 3), however, this was not the case for RFD_{2080} and IMP_{2080}. Protocol 1 was found to have the highest ICC values for RFD_{2080} and IMP_{2080} noted as "high" (ICC = 0.82 to 0.86; CV = 10.5%-11.8%) and "very high" (ICC = 0.91 to 0.93; CV = 11.4%-12.6%) inferences, respectively. Protocol 3 was closer to these values, however showing larger ranges in ICC values, this range magnified even further in protocol 2 (Table 3). Protocol 2 produced the largest ranges in ICC values for RFD_{2080} and IMP_{2080}, (ICC = 0.57 to 0.82; CV = 21.2%-27.4%) and (ICC = 0.40 to 0.63; CV = 21.4%- 30.8%). Finally, PRFD produced consistently higher ICC values (ICC = 0.87 -0.94) and lower CV% (CV = 8.90% -17.6%) than the RFD_{2080} and IMP_{2080} variables across all protocols, however the trend of lower ICC and larger CV% remained with protocol 2.

Table 3: Intrasession reliability measures for three knee extensor protocols

Variable	**Protocol**	**Within-Subject Coefficient of Variation (CV) [95% CI]**			**Intraclass Correlation Coefficient (ICC) [95% CI]**			**Variability**		
		Trial 2-1	Trial 3-2	Trials 3-1	Trial 2-1	Trial 3-2	Trial 3-1	Trial 2-1	Trial 3-2	Trial 3-1
PF (N)	Protocol 1 (n = 32)	3.20 [2.60, 3.70]	3.20 [1.80, 4.10]	4.50 [3.60, 5.20]	0.99 [0.98, 0.99] **Very High**	0.99 [0.98, 0.99] **Very High**	0.98 [0.95, 0.99] **Very High**	Small	Small	Small
	Protocol 2 (n = 31)	7.10 [3.80, 9.20]	3.20 [1.70, 4.10]	5.50 [2.30, 7.40]	0.92 [0.85, 0.96] **Very High**	0.98 [0.97, 0.99] **Very High**	0.94 [0.89, 0.97] **Very High**	Small	Small	Small
	Protocol 3 (n = 31)	3.20 [2.50, 3.70]	3.20 2.50, 3.70]	3.20 [1.70, 4.10]	0.98 [0.96, 0.99] **Very High**	0.98 [0.96, 0.99] **Very High**	0.97 [0.95, 0.99] **Very High**	Small	Small	Small
PRFD (N/s)	Protocol 1 (n = 32)	10.0 [6.90, 12.3]	9.50 [7.40, 11.2]	8.90 [6.50, 10.9]	0.93 [0.86, 0.96] **Very High**	0.93 [0.86, 0.97] **Very High**	0.94 [0.89, 0.97] **Very High**	Moderate	Small	Small
	Protocol 2 (n = 31)	15.2 [11.8, 17.9]	17.6 [11.1, 22.3]	15.8 [10.8, 19.6]	0.90 [0.79, 0.95] **High**	0.83 [0.67, 0.91] **High**	0.82 [0.64, 0.91] **High**	Moderate	Moderate	Moderate

	Protocol 3 (n = 31)	10.0 [7.10, 12.2]	8.90 [6.40, 10.9]	13.4 [8.40, 17.0]	0.91 [0.8, 0.96] **Very High**	0.94 [0.88, 0.97] **Very High**	0.87 [0.74, 0.93] **High**	Moderate	Small	Moderate
RFD_{2080} (N/s)	Protocol 1 (n = 32)	11.4 [8.00, 1.40]	11.8 [6.00, 15.6]	10.5 [7.10, 13.0]	0.82 [0.66, 0.91] **High**	0.83 [0.68, 0.91] **High**	0.86 [0.74, 0.93] **High**	Moderate	Moderate	Moderate
	Protocol 2 (n = 31)	21.2 [10.1, 28.3]	22.1 [13.8, 28.1]	27.4 [18.0, 34.3]	0.82 [0.63, 0.91] **High**	0.76 [0.57, 0.88] **High**	0.57 [0.25, 0.77] **Medium**	Moderate	Moderate	Large
	Protocol 3 (n = 31)	15.5 [10.1, 19.4]	16.4 [11.2, 20.4]	17.9 [9.00, 23.7]	0.81 [0.64, 0.90] **High**	0.85 [0.72, 0.93] **High**	0.80 [0.62, 0.90] **High**	Moderate	Moderate	Moderate
IMP_{2080} (N/s)	Protocol 1 (n = 32)	12.6 [8.40, 15.8]	11.8 [7.50, 14.9]	11.4 [8.40, 13.7]	0.91 [0.83, 0.96] **Very High**	0.93 [0.85, 0.96] **Very High**	0.92 [0.83, 0.96] **Very High**	Moderate	Moderate	Moderate
	Protocol 2 (n = 31)	25.3 [0.00, 36.0]	21.4 [13.7, 27.0]	30.8 [20.1, 38.7]	0.40 [0.09, 0.66] **Low**	0.63 [0.37, 0.81] **Medium**	0.43 [0.11, 0.68] **Low**	Large	Large	Large
	Protocol 3 (n = 31)	17.3 [11.3, 21.7]	19.5 [12.7, 24.5]	20.7 [9.40, 27.8]	0.79 [0.59, 0.89] **High**	0.79 [0.60, 0.89] **High**	0.67 [0.42, 0.83] **Medium**	Moderate	Moderate	Moderate

PF = peak force; PRFD = peak rate of force development; RFD = rate of force development; IMP = impulse; Protocol-1 (Constrained): Isokinetic dynamometer chair + Load Cell Device + 90 degree knee position; Protocol- 2 (Unconstrained): Load Cell + Plinth + 60 degree knee position; Protocol- 3 (Unconstrained): Load Cell + Plinth + 90 degree knee position

Discussion

The purpose of this study was to examine intrasession reliability of not often used kinetic measures collected with a novel load cell device. A secondary focus was on comparing the devices measurement consistency when used with laboratory-grade constraint to its use in a more clinically practical means with no constraint. The main findings of this study were that PF can be reliability collected on all three protocols (inferences "very high"; ICC = 0.92 -0.99; CV = 3.20% - 7.10%), however protocol 2 produced higher variability (CV%) than both protocol 1 and 3. Previous researchers have reported higher force production obtained at approximately 60 degrees due to length-tension and other biomechanical principles imposed on muscle-tendon units[57,67]. While this may be true, the holding of the pretension state at that position, may impact its reliability. This was found to be a trend for all variables, with protocol 2 demonstrating lower ICC values and large variability (CV%) than both protocol 1 and 3 which were at 90 degrees of knee flexion. Similar results were found for PRFD, producing inferences across all protocols

of high to very high (ICC = 0.82 -0.94. Protocol 2 continued to produce lower ICC values (0.82-0.90) with the highest CV% (CV = 15.2% -17.6%0 compared to both protocol 1 and 3.

While RFD_{2080} and IMP_{2080} were found to have 'high' and 'very high' ICC inferences for protocols 1 and 3, however, the CV% remained large (RFD_{2080} CV = 10.5% -17.9%; IMP_{2080} CV = 11.4% - 20.7%). Protocol 1 produced the lowest overall variability, ICC and CV%, followed by protocol 3, and finally protocol 2. Based on these data, specifically the CV%, RFD_{2080} and IMP_{2080} should be explored further in order to better understand these variabilities.

Finally, with respect to the protocol positions, it is likely, although the 60 degree position may be more useful for peak force data, the 60 degree position provided less rigidity due to the position, which would account for the larger variance in means across trials. Furthermore, the 90 degree knee angle was not only more reliable than the 60 degree knee angle, it was subjectively reported as feeling more stable and fixed by participants. ICC values of the current study are consistent with, or greater than previously published reliabilities[1,63,87]. This phenomenon further illustrates RFD to be highly sensitive and responsive to system rigidity and may be a limiting factor for RFD metrics[57,67]. Therefore, knee angle should be considered when using the load cell for force capabilities.

Limitations

It is acknowledged that there are limitations to the current study. First, similar to previous reports, nuances and limitations in collecting RFD and other rapidly generated force variables are difficult to fully eliminate. These include the limitations associated with pretension prior to contractions. Previous researchers have identified reductions in force onset accuracy in performing isometric tests associated with a pretension state before the initiation of the force output[1]. Nonetheless, the study design and apparatus offered no other plausible solutions to this dilemma. It should also be noted that while a convenience sample population was recruited, an overwhelming majority of these individuals were very active regarding physical exercise, and may present different outcomes when compared to less active counterparts. Finally, it is worth acknowledging that the data analysis procedures used in this study also present potential limitations to practical use. The method used to identify contraction onset and subsequent 20-80% PF window was effective for the majority of testing sessions. However, in poor performance trials, specifically those with multiple force peaks within the testing window, the algorithm was occasionally less accurate than manual selection strategies, leading to a manual review of each trial for quality assurance. If this device is to be used in clinical medicine, it must be explored in situations that resemble such situations to enhance its potential.

Conclusion

The collection of PF and PRFD can be completed reliably between trials when using a constrained method (such as an isokinetic dynamometer fixation set up) or on an unconstrained protocol (such as a physiotherapy plinth) when the knee is tested at 90 degrees. These findings would suggest that appropriate fixation, meaning rigid, is better for reliability testing for these metrics, and that the 90 degree knee position is better suited for that criteria. Practitioners should be confident in the between-trial (intrasession) reliability of this novel load cell in any of the reviewed protocols for PF and PRFD, however specific attention should be applied for the variables RFD and IMP, by which these data recommend using 90 degrees of knee flexion and a more constrained set up.

CHAPTER FOUR - STUDY 2

Intersession reliability of knee extension kinetic variables using a load cell device on varying degrees of fixation rigidity.

Prelude

In the previous chapter we were concerned with finding the intrasession reliability of peak force (PF), rate of force development (RFD), peak rate of force development (PRFD), and impulse (IMP) using a load cell device with an isometric knee extension contraction. This was completed in various protocols, which varied in degrees of fixation, or constraint, which represented a clinically applicable set-up versus a more laboratory type set-up. PF had the highest reliability, irrespective of the protocol used, when compared to the other variables, with PRFD having comparable outputs. With the remaining variables, RFD and IMP, protocol 1 (representing the most constrained of the protocols, and at 90 degrees of knee flexion) had notably higher ICC, and lower CV%, values compared to protocol 2. While protocol 1 produced ICC inferences for RFD and IMP of high to very high, the CV% were large (>10% for both variables). Therefore, caution is recommended with these two kinetic variables according to these results. Moving into study 2, it is likely more important with clinicians to understand the variability of a measure over time (test-retest or intersession reliability). This helps the practitioner understand and interpret "real" changes associated with their assessments and associated interventions. Therefore, the purpose of this study was to explore the intersession reliability of the aforementioned kinetic variables.

Introduction

The processes of rehabilitation and performance are built on the ability to assess various factors and monitor change over time. The interpretation of these changes helps direct programming, help justify intervention strategies, and ultimately serve as criteria for progression[1-7]. In physical medicine, such as physiotherapy, athletic training, and chiropractic care, the more common factors revolve around metrics of tissue performance, most commonly range of motion, force production, and functional movement tests[1-7]. Each metric provides unique information that can be compiled to produce a profile of performance for the individual, and provide a more robust representation of status and outcome[1-7].

Regardless of the assessment, the accuracy of the tool, device, or task by which testing is accomplished, are fundamental for success. Accuracy of a given test or metric includes reliability, representing how stable and consistent it is, and validity, representing how meaningful the data produced are with respect to the question of interest[260]. Colloquially, this can be understood as how much error is in the metric within multiple tests and on multiple testing sessions (reliability), and does the metric adequately measure and represent what it says it is intending to do (validity). The former domain, reliability, is the focus of this study, specifically intersession reliability (the consistency of a given metric across multiple time points) for areas of force-time characteristics within maximal isometric contractions.

Force-time characteristics are valuable set of physical performance measurements that rationalize force production for given domains of time, epochs. These epochs are constructed to represent certain tasks, and thus may provide better insight into the ability of an individual than force production capabilities, alone[1,9]. The force-time variables of interest with this study are RFD and IMP. RFD represents the change in force over the change in time, and is visualized as the slope of the curve where force is expressed for a given epoch[1]. IMP for the same given epoch, represents the amount of force produced for a given time, or the area under the cure[1]. These two domains are gaining clinical popularity[9]. Increases in RFD and IMP have been associated with improvements in a variety of human activities, including certain daily tasks (such as balance and walking speed[29-31]), as well as a sport tasks (such as sprint speed and weightlifting capacity[27,28]). They have been also found to provide better insight into muscle-tendon unit stiffness[17,18], the physiology of the muscular unit[10,19], nervous system capacity[20-22], and psychologic confidence[1,23-26]. Therefore, the use of RFD and IMP may be of unique value for the scope of physical medicine.

The collection process of RFD and IMP, specifically in regards to the aforementioned tasks, requires specific equipment and analysis software. This is likely a major factor in why RFD and IMP have remained relatively unused in physical medicine, despite its empirically reported benefits. At the crux of

this limitation is device availability, affordability, and practicality[2-9]. Devices suited to collect this data, such as isokinetic dynamometers or force plates, pose barriers to implementation for many clinical practitioners, and are often only located in higher performance facilities or larger hospital systems. Recent technological developments have seen a load cell device become a potential alternative to these larger devices. The load cell device is more portable device, being more compact and mobile, and also a more affordable option, and therefore a viable option to quantify force-time data.

As with any new device, technology, or metric, empirical investigation must take place in order to establish its accuracy (validity and reliability). The accuracy of commercial isokinetic dynamometers and force plates are well established[57,58,67,68], however the available evidence for a load cell device in relation to RFD and IMP are limited[1]. Therefore, the primary aim of this study was to quantify the intersession reliability of RFD and IMP measured using load cell technology collected via an isometric knee extension contraction in healthy individuals. This was completed using various protocols (a constrained position with rigid fixation and an unconstrained position with limited fixation on a physiotherapy plinth), which were designed to represent a more laboratory set-up (constrained) versus a more clinical set-up (unconstrained).

Methods

Experimental Design

A cross-sectional repeated measures design was employed to determine the consistency of the dependent variables of interest. Force-time data was collected during a maximal voluntary isometric contraction (MVIC) knee extension task using a custom-designed prototype load cell (SPRINZ Laboratories, Auckland University of Technology) device in different protocols. All data were collected by a single rater. All participants attended three data collections sessions (7-10 days apart), which consisted of a standardized warm-up and then the recording of three explosive MVICs on the three different protocols. The same protocol was replicated on all testing occasions; however, the order of the testing protocols was randomized for each session.

Participants

Twelve healthy subjects volunteered for this study, the characteristics of which are summarized in Table 4 expressed as mean ± standard deviation. All participants reported their right limb as dominant (defined as the leg they would use to kick a ball). All participants were healthy, as defined by the PAR-Q questionnaire, with no current health conditions that would limit strenuous exercise and reported being able to complete a maximal knee extension. Participants were excluded if they had any prior surgical

intervention that would limit maximal knee extension performance. The participants were informed that participation was voluntary and could withdraw at any time. Ethics approval for this study was obtained from the Auckland University of Technology Ethics Committee. Before testing all participants gave written informed consent.

Table 4: Participant demographics (mean ± standard deviation)

		Protocol 1 *(IsoK + Cell 90°)*	**Protocol 2** *(Plinth + Cell 60°)*	**Protocol 3** *(Plinth + Cell 90°)*
Subjects (n)	Male	4	5	5
	Female	6	6	5
Height (cm)	Male	172 ± 3.70	172 ± 3.40	172 ± 3.40
	Female	162 ± 5.30	162 ± 5.30	164 ± 4.30
Bodyweight (kg)	Male	83.5 ± 12.8	84.6 ± 11.30	84.6 ± 11.30
	Female	61.5 ± 7.20	61.5 ± 7.20	63.4 ± 6.10
Age (years)	Male	28.2 ± 5.10	27.4 ± 4.80	27.4 ± 4.80
	Female	32.2 ± 6.70	32.2 ± 6.70	29.6 ± 2.70
Right Lever Length (cm)	Male	34.2 ± 3.40	33.8 ± 3.10	33.8 ± 3.10
	Female	34.0 ± 1.20	34.0 ± 1.20	34.4 ± 0.80

Equipment

The Load Cell device was a wireless force measurement system comprising of a load cell device with wireless telemetry, and an intuitive software package developed internally(SPRINZ Laboratories, Auckland University of Technology).

Procedures

Three different protocols were collected to determine the effects of body constraints and knee angle on the reliability of the measures. These protocols were designed to compare laboratory and clinical environments. Protocol 1 was defined as the Load Cell + Constrained + 90 degrees (see Figure 11.a). The participant was seated upright in the chair of the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY) at a hip angle of 85º, with shoulder, waist, and thigh straps affixed to reduce body movement during contractions. The load cell was tethered to the isokinetic dynamometer and the individual's lower leg ~two centimetre (cm) superior to the lateral malleolus using a steel chain. The knee was measured and maintained at 90º, throughout the set-up and trials, by shortening or lengthening the chain. The chair was adjusted to maintain both the center of rotation just beyond the edge of the chair and that the line of force production was maintained in-line the orientation of the load cell. The 60º knee flexion position, as seen

and tested in protocol-2 (description below), was not collected on the isokinetic dynamometer due to the inadequacy of appropriate angular fixation. The computer, with software visible, was placed directly in front of the participant to be used for practice trials, feedback, and the pretension threshold. The pretension mark for this device and protocol was 120 Newtons (N), while the collection threshold was 160 N i.e., the trial initiation was established once the force produced was >160 N.

Figure 11: Images of protocols 1, 2, and 3; 11.a: protocol 1= Load Cell + Constrained + 90°; 11b: protocol 2 = Load Cell + Unconstrained + 60°; Not Shown: protocol 3 = Load Cell + Unconstrained + 90°.

Protocol 2 and 3 (see Figure 11.b) both involved the use of a physiotherapy plinth, rather than the use of the isokinetic dynamometer chair, and were subsequently identified as “unconstrained”. Protocol 2 utilized the Load Cell + Unconstrained+ 60 degree knee position while protocol 3 utilized the same Load Cell + Unconstrained set up but at 90 degrees. For both protocol 2 and 3, the participant was seated on the edge of a clinical plinth, and allowed to self-select a position while meeting the following criteria: 1) the participant must maintain this position throughout the trials; 2) the participant must hold the sides of the table; and, 3) the participant must shift towards the side of the table being tested so that the line of force aligned to the fixation point that was previously located. Once seated and comfortable, the participant was sat on the edge of the plinth two cm superior to the lateral malleolus using a low compliance, steel chain, and a towel was placed under the distal thigh between the thigh and table to account for discomfort from the sharp plinth edge. The participant was asked to create a submaximal force (to achieve the true testing position and remove any slack in the chain) and the knee was measured to either 60º (protocol 2) or 90º

(protocol 3) respectively, according to the intended position. Every participant completed both knee joint angles positions; however, the order was randomized between sessions. The chain to table fixation was different for the two knee positions to accommodate for the angle of force production. Throughout practice trials, the participant was allowed to move and change position, however, once the testing began, no further changes were allowed, and the participant's position was recorded for future testing sessions. As with protocol 1, the computer monitor was placed within view of the participant for purposes of practice trials, pretension, and feedback.

Each participant warmed up by cycling at low to moderate resistance using a self-selected pace for three to five minutes. They were then placed in the constrained protocol for familiarisation. Familiarisation occurred at every session using the constrained protocol, regardless of the randomized testing order, and included a series of progressive, ascending force output isometric knee extension trials, which culminated with one trial at maximal effort. The participant was given verbal and visual feedback during these trials regarding performance and education was implemented in cases of confusion or to troubleshoot positioning. After familiarisation trials were completed, the participant was asked to dismount the chair, and a five-minute rest commenced before the initiation of data collection. As part of the familiarization and practice trials, specific instruction and verbal cueing were explained and used. The term 'fast' in "fast and hard" was consistently emphasized throughout all testing occasions, which is necessary when collecting RFD and IMP metrics as opposed to maximal force[156]. The participant was given strong verbal encouragement throughout each trial.

After the familiarization trials and five-minute rest, the participant was then placed into one of the assigned protocols randomly. The participant was allowed up to five practice trials including verbal and visual feedback, and the participant was encouraged to complete at least one maximal effort contraction before finishing the practice trials. For testing trials, the participant was told to achieve the determined pretension state and hold at this level for two seconds by slowly extending the knee into the strap while observing the force-time curve on the monitor. Once the force curve was steady at the pretension threshold, the primary investigator (PI) would begin a count down from 3 ("3-2-1-Go-Go-Go-Go-Go-Stop"). The participant was instructed to begin the MVIC at any point after "1" and maintain the contraction until told to "stop".

Each participant completed three trials at each protocol. Due to the short duration of trials, the rest between repetitions was set at 10 to 30 seconds based on participant preference as described by previous researchers [222]. The force-time curve was visually inspected for large deviations in force production (>250

N from prior trials), or notable countermovement, or inconsistencies in the pretension state. If evident, these false contractions were removed, and the trial repeated. The testing order was dictated by random order assignments for each participant.

Data Processing

Raw unfiltered force-time data was exported for subsequent analysis in CSV format. Only right leg (dominant leg) data was utilised for analysis. The data was then imported and analyzed in MATLAB (MathWorks, Natick, MA), using a custom algorithm. Each trial was trimmed to length to include a pretension period of at least 0.5 seconds, force onset, isometric contraction for at least one second, and a force offset. The onset of force was defined as an increase in force that was greater than three standard deviations (3 SD) of force calculated from the 350 ms pretension window within one second before the contraction[1,71,72,253]. The onset of force was calculated as the first 3 SD threshold crossing from the location of peak force working backwards. Outputs were visually assessed for methodological outliers, which were removed from the analysis. PF was determined as the absolute maximum force recorded during the entirety of the two-second contraction; and 20% and 80% of this peak force were calculated. All further variables of interest were then determined from within the time interval created by the 20%-80% peak force thresholds, as described by Cobian et al. (2017) and Dudley-Javoroski et al. (2008)[232,233] (Figure 12). Rate of force development (RFD_{2080}) was the average slope over the epoch (F/t) and impulse (IMP_{2080}) was the area under the force-time curve, during the defined window. PRFD was calculated using a 10 Hz 4th order low-pass Butterworth filter.

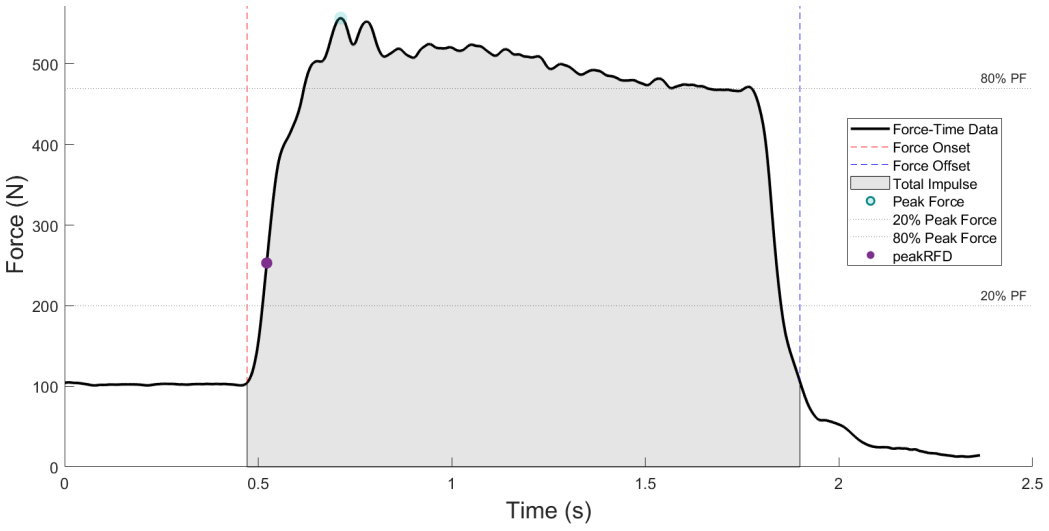

Figure 12: Visual representation of the force-time data for the load cell. This figure outlines the onset of contraction methodology used (reverse 3 SD method). Note: The large arrow describes the direction by

which the application of the 3 SD pretension window threshold was applied. The blue dot highlights the peak force in the trial

Statistical Analysis

All statistical analysis was conducted using RStudio IDE (Version 1.4.869, 2009 – 2020 RStudio, PBS). The statistical analysis explored the reliability of three sessions for each protocol. Each subject completed a series of at least three trials at each protocol, which were averaged and used for further analysis. If less than three trials were conducted or the subject did not attend all sessions, the subject was removed from any further analysis. Outlier analysis was conducted using intrasession, intra-subject z-scores. Boxplots were used to visually check for outliers of the calculated z-scores (rstatix version: 0.6.0). Only extreme outliers were removed from the analysis. Normality of each intersession variables was confirmed using Shapiro Wilks test. Mean and standard deviations were calculated. No significant inter-limb differences were observed and so the analysis was of the right limb only. There was no gender bias found, thus genders were combined for all analyses. The within-subject coefficient of variation (CV), and intra-class correlation coefficient (ICC) (two-way mixed effects, absolute agreement, type = single) were used to explore systematic change, absolute and relative consistency respectively. Within-subject CV's were calculated using the root mean square approach[259]. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability when either the ICC > 0.67 or the CV < 10%, but not both, and small variability when ICC > 0.67 and CV < 10%.[254,255]

Results

Table 5: Intersession mean, standard deviation and percent changes with 95% CI

Variable	Protocol	Mean ± SD			Within-Subject Percent Difference in Means (%) [95% CI]	
		Session 1	Session 2	Session 3	Session 2-1	Session 3-2
PF (N)	Protocol 1 (n = 10)	535 ± 89.6	489 ± 94.5	485 ± 100	10.7 [0.91, 20.5]	1.72 [-6.1, 9.4]
	Protocol 2 (n = 11)	554 ± 14.0	490 ± 129	540 ± 127	14.4 [0.91, 27.9]	-8.74 [-17.4, 0.12]
	Protocol 3 (n = 10)	534 ± 10.0	533 ± 135	529 ± 117	1.6 [-4.42, 7.66]	0.64 [-5.7, 6.8]
PRFD (N/s)	Protocol 1 (n = 10)	3367 ± 873	2878 ± 872	2912 ± 1005	21.8 [0.47, 43.3]	1.02 [-12.0, 14.0]
	Protocol 2 (n = 11)	3414 ± 1335	3013 ± 1131	3255 ± 1104	20.4 [-16.5, 57.2]	-5.64 [-20.5, 9.3]
	Protocol 3 (n = 10)	3358 ± 1065	3391± 906	3384 ± 1093	0.64 [-19.4, 20.6]	5.97 [-16.3, 28.2]
RFD_{2080} (N/s)	Protocol 1 (n = 10)	2164 ± 536	1903 ± 613	1959 ± 641	18.4 [-1.04, 37.9]	-1.89 [-12.1, 8.4]
	Protocol 2 (n = 11)	2446 ± 990	2281 ± 1050	2256 ± 862	15.8 [-12.9, 44.6]	3.13 [-20.1, 26.2]
	Protocol 3 (n = 10)	2381 ± 878	2404 ± 617	2458 ± 712	1.02 [-23.8, 25.9]	3.93 [-21.8, 29.6]
IMP_{2080} (N/s)	Protocol 1 (n = 10)	31.4 ± 9.20	29.8 ± 10.9	27.3 ± 7.30	11.9 [-11.0, 34.7]	8.74 [-8.3, 25.8]
	Protocol 2 (n = 11)	35.6 ± 18.9	27.4 ± 12.4	34.4 ± 16.2	39.5 [-2.81, 81.9]	-15.4 [-37.9, 7.00]
	Protocol 3 (n = 10)	31.0 ± 13.7	27.9 ± 10.7	27.1 ± 8.70	18.0 [-17.1, 53.1]	3.52 [-11.2, 18.2]

PF = peak force; PRFD = peak rate of force development; RFD = rate of force development; IMP = impulse; Protocol-1 (Constrained): Isokinetic dynamometer chair + Load Cell Device + 90 degree knee position; Protocol- 2 (Unconstrained): Load Cell + Plinth + 60 degree knee position; Protocol- 3 (Unconstrained): Load Cell + Plinth + 90 degree knee position

Table 6: CV, ICC, and 95% CI

Variable	Protocol	Within-Subject Coefficient of Variation (CV%) [95% CI]		Intraclass Correlation Coefficient (ICC) [95% CI]		Variability	
		Session 2-1	Session 3-2	Session 2-1	Session 3-2	Session 2-1	Session 3-2
PF (N)	Protocol 1 (n = 10)	11.0 [9.00, 13.0]	7.00 [4.00, 9.00]	0.67 [0.12, 0.90]	0.84 [0.47, 0.96]	Large	Small
	Protocol 2 (n = 11)	14.0 [0.00, 20.0]	12.0 [1.00, 17.0]	0.77 [0.22, 0.94]	0.74 [0.29, 0.92]	Moderate	Moderate
	Protocol 3 (n = 10)	6.00 [3.00, 7.00]	6.00 [5.00, 8.00]	0.93 [0.74, 0.98]	0.93 [0.75, 0.98]	Small	Small
PRFD(N/s)	Protocol 1 (n = 10)	19.0 [0.00, 27.0]	12.0 [5.00, 17.0]	0.66 [0.07, 0.91]	0.78 [0.31, 0.94]	Moderate	Moderate
	Protocol 2 (n = 11)	25.0 [0.00, 37.0]	18.0 [0.00, 28.0]	0.50 [-0.07, 0.83]	0.72 [0.27, 0.92]	Large	Moderate
	Protocol 3 (n = 10)	22.0 [0.00, 32.0]	17.0 [0.00, 25.0]	0.61 [-0.04, 0.89]	0.78 [0.33, 0.94]	Large	Moderate
RFD_{2080} (N/s)	Protocol 1 (n = 10)	18.0 [4.00, 25.0]	10.0 [0.00, 15.0]	0.74 [0.21, 0.93]	0.84 [0.47, 0.96]	Moderate	Small
	Protocol 2 (n = 11)	23.0 [0.00, 33.0]	24.0 [13.0, 32.0]	0.60 [0.03, 0.87]	0.63 [0.06, 0.89]	Large	Large
	Protocol 3 (n = 10)	27.0 [0.00, 40.0]	20.0 [6.00, 27.0]	0.48 [-0.24, 0.84]	0.66 [0.07, 0.91]	Large	Large
IMP_{2080} (N/s)	Protocol 1 (n = 10)	20.0 [12.0, 25.0]	16.0 [11.0, 19.0]	0.64 [0.06, 0.90]	0.72 [0.25, 0.92	Large	Moderate
	Protocol 2 (n = 11)	35.0 [16.0, 47.0]	27.0 [19.0, 33.0]	0.44 [-0.09, 0.80]	0.62 [0.10, 0.88]	Large	Large
	Protocol 3 (n = 10)	25.0 [0.00, 35.0]	15.0 [0.00, 23.0]	0.61 [0.03, 0.89]	0.88 [0.60, 0.97]	Large	Moderate

PF = peak force; PRFD = peak rate of force development; RFD = rate of force development; IMP = impulse; Protocol-1 (Constrained): Isokinetic dynamometer chair + Load Cell Device + 90 degree knee position; Protocol- 2 (Unconstrained): Load Cell + Plinth + 60 degree knee position; Protocol- 3 (Unconstrained): Load Cell + Plinth + 90 degree knee position

In terms of the PF there seems a systematic change in the mean for all three protocols, protocol 2 having the greatest change (14.4% (sessions 2-1) and -8.74% (sessions 3-2)). Protocol 3 exhibited the best absolute (CV = 6.00%) and relative consistency (ICC = 0.93) across both testing occasions, producing the smallest variability inferences.

There seemed a systematic decrease in peak RFD across protocol 1 and protocol 2 across testing occasions, however, protocol 3 had the smallest change in the mean, which were in reverse to the other

two conditions (3.77% to 8.21%). The CVs (10.62 to 13.35%) were all better on the Day 3-2 testing, the lowest variability associated with protocol 1. All ICCs were greater than 0.70 with the Day 3-2 comparisons (0.72 to 0.83), the highest ICC associated with protocol 3 protocol.

The change in mean of the RFD_{20-80}, decreased between testing occasions for protocol 1 and protocol 2 conditions, however, protocol 3 once more had the smallest change in the means (3.83 to 6.79%), which were in reverse to the other two protocols. The change in CVs between testing occasions was mixed with ~5-7% decreases in protocol 1 and protocol 3 CVs, but protocol 2 increasing by 5%. Protocol 1 had the lowest CV (10.1%). Protocol 1 and protocol 3 improved over testing (ICC > 0.70, Day 3-2), the greatest ICC associated with the protocol 3 protocol.

With regards to IMP_{2080}, there was a change in the mean for protocol 2 and protocol 3 (~18-20%), whereas protocol 1 was stable (~16%) between testing occasions. All CVs decreased between testing occasions the largest decrease (~4%) in protocol 3(CV = 13.9%). The ICCs across all variables and testing occasions were less than 0.7.

Discussion

The instability of RFD, as a representation of a variety of neuromuscular factors, has been well established and described in large reviews[1,7,8], and stands as a hallmark consideration when exploring RFD, while peak force appears to be a much more stable, and dependable metric[1,7-9]. With respect to these data, it seemed that the RFD measures might have benefitted from greater familiarization given the systematic change between testing occasions. Previous studies and reviews have highlighted the importance of familiarization in regards to RFD trials, with familiarization becoming a necessary and vital component of RFD collection[1,5,7,8,10]. These studies utilized a single familiarization session, prior and independent from data collection. While this is well supported, the clinician may not have the ability to incorporate a testing session prior to data collection. With this in mind, this study incorporated a familiarization session 15 minutes prior to data collection in each session. This certainly may have some impact on these data; however, the RFD values are within the variability of other reports and publications[1,5,7,8,10]. The systematic change could be explained in terms of biological variation, that is the RFD measures much more sensitive to change in biological status, or technological variation, that is RFD affected to a greater extent in subtle changes in the methodological set up, as compared to PF and IMP_{20-80}.

Protocol 3 PF was the only variable to have acceptable absolute and relative consistency. Specifically, in regards to PF, it is well known that PF represents a fairly stable metric[1,2,11-14], and these data support previous findings. This is reassuring for the practitioners who want to measure peak knee extensor force from their plinth, as the procedures detailed in this study were more reliable than a fully restrained isokinetic setup. Regarding the knee position, it appears that the use of the 90° position is more consistent than 60°. In clinical practice, there is no agreed upon testing position, as the position is generally determined by a variety of variables, such as safety of the graft in a client post anterior cruciate reconstruction, the position of optimal length tension and therefore maximal force production, or the position most representative or associated with symptoms (like those seen in tendonopathy). While this study only observed two positions, these two positions represent two of the most common positions of force testing. Findings from this study suggest that the reliability of the peak force data collected at 60° are inferior to those collected at 90°. This is likely due to the rigidity of the set-up, ultimately corresponding to improved force transmission and potentially other physiologic factors[15].

RFD_{20-80} produced a different profile than that of PF. All variables, apart from protocol 2 RFD_{20-80}, had moderate variability (ICC>0.67), and were unsurprisingly lower than PF. The scatter plots were investigated to determine if there were bi-polar trends given the male-female cohort that may have artificially inflated the ICC, however, such trends were not observed. Interestingly lower variability was associated with the Isok 90° condition when measuring RFD measures, however better consistency was observed for the PF and IMP measures with protocol 3 protocol. This seems logical in that if the RFD measures are more sensitive to subtle changes in methodological set up, then having subjects full constrained in an isokinetic dynamometer chair would certainly reduce any movement artefact that could influence variability of the measures. On the other hand, it is useful to know that PF and IMP_{20-80} can be measured with better consistency on a plinth as compared to a fully constrained approach. It is recommended however, given the results of this study, that the protocol 2 protocol should be used with caution. The importance of system, testing, and procedural rigidity is well documented, as any compliance can substantially impact the kinetic profile, especially with respect to RFD[1,63,64,87]. Typically, this is controlled by employing a more laboratory and constrained testing methodology, however, these procedures present a problem for clinical practicality. This study was designed to provide initial data related to a strictly clinical scenario and compare these data to previously reported values. Recognizing that these data are similar, these findings provide a valuable potential for the more practical organization of kinetic data outside of laboratory avenues. It is important to acknowledge that no agreed upon method for RFD or IMP exist. This data suggests that a more acute joint angle, 90°, may provide a more rigid environment and thus a higher reliability value, although this value remains only a ‘moderate’ inference.

While these findings are similar to previously published RFD reliability results [66,108,113,142,221,236], future research into RFD should continue to develop testing procedures to improve the veracity of this measurement. Furthermore, this study utilized a unique method for creating the testing window, which should warrant consideration when comparing data across studies. Nonetheless, caution needs to be exercised as the CVs for all the variables apart from PF, for the most part was greater than 20%, indicating a great deal of biological and/or technological variability between testing occasions with these measures.

Limitations

This study is not without limitations. As reported by previous studies, nuances, and limitations in the procedure of collecting RFD and other explosive force variables are difficult to fully eliminate. This study utilized a pretension state before the initiation of the force output. The ability to maintain a stable pretension state was difficult per reports from participants, and this could have impacted the force production capabilities. While this is known as a potential limitation, the study design and apparatus offered no plausible solution to this dilemma. Although differences between the constrained and unconstrained methods were part of the study design. Padding, in the form of a folded towel, was required on the plinth due to discomfort during maximal force events caused by sharp edges. This added padding would likely impact the results in a minor way, introducing a challenge in standardizing this methodology. Ultimately, a decision must

Conclusion

Given better familiarization it may be that load cell technology could collect PF, RFD and IMP reliably on a plinth. This certainly reinforced by the finding that the only measure displaying small variability (PF) was collected with protocol 3. However, with respect to RFD and IMP, continued exploration in methodologies, including familiarization, set-up, and analysis are warranted before recommendations for clinical use can be suggested. Given the limitations, further research is needed to address some of the identified issues to determine if the protocol used in this study can be refined to produce acceptable absolute and relative consistency especially with the RFD and IMP measures.

CHAPTER FIVE - STUDY 3

The validity of kinetic variables collected via the load cell apparatus versus an isokinetic device.

Prelude

In Chapter 3, it was found that peak force (PF) and peak rate of force development (PRFD) can be collected using a load cell device with high to very high ICC values (PF ICC = 0.92 -0.99; PRFD ICC = 0.82 - 0.94). PF CV% was found to be fairly small (CV = 3.20% -7.10%) with protocol 2 being responsible for the highest CV%, while PRFD produced acceptable, all be it larger CV% (CV = 8.90% - 17.6%) again with protocol 2 being the largest variability. Therefore, it can be recommended that PF and PRFD are reliable within session when collected at 90 degrees of knee flexion. This trend continued with rate of force development (RFD) and impulse (IMP), being that the 90 degree knee position (protocols 1 and 3) produced higher ICC values, however, all protocols produced large CV% (RFD CV = 10.5% - 27.4%; IMP CV = 11.4% -30.8%) with protocol 2 being the largest CV%. Chapter 4 expanded on Chapter 3 in exploring between session reliability of the aforementioned kinetic variables. PF was the only variable to have acceptable reliability when collected between sessions, over a 7-10 day window (PF ICC = 0.67 -0.93 and CV% = 6.00% - 14.0%). CV% were notably larger and ICC values were notably smaller for the remaining kinetic variables. Caution should be taken when attempting to compare kinetic data across time points, except in the case of PF. Chapters 3 and 4 were designed for intra- and inter- session reliabilities. Another important metric to understand the value of testing is establishing the validity of certain measures. Comparing emergent technology to “gold standard” technology is how new technology is validated. The purpose of this study therefore was to compare kinetic data captured via load cell technology to “gold standard” isokinetic technology. The outcomes of these three experimental chapters could be useful to identify the accuracy of field testing or clinical testing protocols, help future researchers and clinicians establish clinical normative data sets, aid in the assessment of rehabilitation progression, and potentially play a substantial role in determining readiness and risk assessment in knee conditions.

Introduction

Rate of force development (RFD) (the slope of a time interval within a force-time curve (Newtons/seconds), and impulse (IMP) (the integral of force and time) are valuable components of fore production capacity and characteristics[1,61,64]. When collected at early force onset production, these metrics can translate practically into the ability of a motor unit to quickly develop force[1,61,64]. These metrics have been shown to be valuable for quality of life[121,122], and are important considerations for elderly, neurologically compromised, or at-risk populations[22]. It has been proposed, along with a currently evolving state of empirical data, that RFD/IMP can better predict functional abilities compared to maximal strength assessments, especially in the case of inter-limb asymmetry[64,123-125]. These activities include gait speed, which was noted by Suetta et al. (2004) to be more closely associated with capabilities of RFD/IMP rather than maximal strength in elderly individuals after hip replacement[124,125], and power production by the musculature of the back during lifting tasks[54]. RFD/IMP has also been strongly associated with prevention of falls, or the maintenance of balance, as the stabilizing process of the body occurs in very short, rapid contractions[64,108], and has been shown to provide better overall insight into the stiffness of the muscle-tendon unit[18,19], the physiology of the muscular unit[9,20], the capacity of the neural system[21,22], and psychologic confidence[10-13,23,24].

The methodologic collection of RFD/IMP data in clinical science can be quite difficult. A primary consideration of RFD/IMP is related to availability and practicality of the technology and equipment needed to explore explosive force, and the back-end analytics of this data. Appreciating the normal variability in RFD/IMP data, the corresponding device must contain extremely sensitive, high frequency, components in order to record this data accurately. The isokinetic testing apparatus, arguably the gold standard device in joint/muscle specific force testing[32-34], offers excellent data collecting potential, being able to collect a variety of valuable kinetic information. However, this device is expensive when compared to other force assessment tools, such as strain gauges and load cells, and also poses substantial problems regarding portability and availability, and thus not likely to be available for most coaches and performance staff. Furthermore, in regards to data processing and analytics, there is inconsistency in the specific epochs and processing methods. In many of these publications, it involves manual inspection of the trials and data[1,22,62,63], which again limits its useability outside of a laboratory setting.

Sports performance and physiotherapeutic staff often lack affordable, portable, and clinically useful tools to adequately measure and track kinetic force variables from sites such as the knee. While a variety of testing mediums and tools are available, the load cell has the potential to offer a lower financial price point, greater portability, and therefore higher utility for assessing neuromuscular function. Limited data

exists with respect to the validity of such technology, specifically in assessing time dependent data such as RFD/IMP. Therefore, this study intended to explore the use of a load cell as a clinically practical alternative as compared to an isokinetic testing device in investigating knee extension kinetic variables.

Methods

Participants

Twenty-six subjects (12 male and 14 female), age 32.0±8.90 years, height 170±9.90cm, weight 74.8±17.5kg, were recruited for the study. All subjects were healthy individuals with no current health conditions that would limit strenuous exercise, or the ability to complete maximal knee extensions. Subjects were also excluded if they had prior surgical intervention that would limit knee extension performance, or reported any pain throughout the trials. All subjects reported their right leg as dominant (kicking leg).

Study Design

A single-session, cross-sectional study design was implemented, comparing various kinetic variables during maximal voluntary isometric contraction (MVIC) knee extension tasks on a load cell device versus an isokinetic device. These two data collection tools were evaluated using three protocols under which a range of kinetic variables were collected. Subjects completed three, explosive, maximal voluntary isometric contractions (MVIC) of the knee extensors for each protocol. Testing was completed bilaterally for all subjects, however only the right leg data was used for analysis. Order of testing layouts was randomized for each subject and all data was collected by a single rater.

Testing Equipment

The load cell device was a wireless force measurement system that consisted of a load cell, Bluetooth connectivity, and an internally designed software package (SPRINZ Laboratories, Auckland University of Technology) sampling at 1000 Hz. The computer, with software visible, was placed directly in front of the subject to be used for practice trials, feedback, and for the pretension threshold. The pretension mark was set to 120 Newtons (N), while the collection threshold was set to 160 N (i.e., the trial initiation was established once the force produced was above 160 N).

The isokinetic device (Humac Norm; CSMi; Lumex, Ronkonkoma, NY) was used as the gold standard for data collection. The isokinetic dynamometer sampling rate was increased to 1000 Hz through custom software (Labview; National Instruments, New Zealand) to match the sampling frequency of the load cell, and improve accuracy of RDF and IMP calculations as per previous research[1]. The pretension threshold

for this device was set at 40 Nm (torque), which was reported subjectively as similar to the 120 N (force) used with the load cell. The collection threshold for this protocol was 50 Nm.

Procedure

Five data collection protocols were implemented in this study. Each collection made use of either the isokinetic dynamometer or the portable load cell to collect data, in either constrained or unconstrained positions. Kinetic variables were collected at both 60 and 90 degrees except for the load cell in the constrained format under which only 90 degrees was able to be collected due to physical limitations of the set up. Data was collected using 5 'protocols'. These protocols involved varying degrees of knee flexion angle and constraint, or rigidity, designed to compare laboratory and clinical environments.

Protocol 1: Load cell, constrained at 90º

Protocol 1 (Figure 13.a) consisted of the isokinetic device chair and base, the load cell, and 90º knee flexion position. The aim of protocol 1 was to restrict movement of the participant in an effort to match protocol 5, the use of the isokinetic dynamometer under the same conditions to provide an ideal comparison between the two measurement devices. The subject was seated upright in the chair of the isokinetic dynamometer at a hip angle of 85º, with shoulder, waist, and thigh straps to reduce body movement during contractions. The load cell was affixed to the isokinetic dynamometer and to the individual's lower leg ~two cm superior to the lateral malleolus using a low compliance, steel chain. The knee was measured and maintained at 90º, throughout the set-up and trials, by shortening or lengthening the chain. The chair was adjusted to maintain both the center of rotation just beyond the edge of the chair and that the line of force production was maintained in-line with the orientation of the load cell. The subject was instructed to place their non-testing limb behind the counterforce pad and to use the handles on both sides to further reduce body movement.

Protocols 2 and 3: Load cell, unconstrained at 60º and 90º

Protocols 2 and 3 consisted of a clinical plinth (table) and load cell with contractions at both 60º (protocol 2-Figure13.b) and 90º (protocol 3- not shown) of knee flexion. These protocols were designed to replicate the application of the portable load cell technology in a practical setting, such as a physiotherapy clinic. The subject was seated on the edge of a clinical plinth, and allowed to self-select a position while meeting the following criteria: 1) the subject must maintain this position throughout the trials; 2) the subject must hold the sides of the table; and, 3) the subject must shift towards the side of the table being tested (the line of force must be in line to the fixation point which was located towards the side of the table). Once seated and comfortable, the subject was fixed to the table at ~two cm superior to the lateral malleolus using a

low compliance, steel chain. A towel was placed under the distal thigh between the thigh and table to reduce discomfort during expressions of maximal force. The table height was adjusted in order to maintain a 60º or 90º line of force to the angle of fixation. Throughout practice trials, the subject was allowed to move and change position, however once the testing began, no further changes were allowed, and the subject's position was recorded for future testing sessions.

Protocols 4 and 5: Isokinetic dynamometer, Constrained, 60º and 90º

Protocols 4 and 5 had the subject seated upright in the chair of the Isokinetic dynamometer at a hip angle of 85º, with shoulder, waist, and thigh straps to reduce body movement during contractions. This highly restricted method and the use of the isokinetic dynamometer for collecting isometric force is considered the gold standard for comparison to the load cell. The subject was adjusted in the device in order to place the joint line at the center of dynamometer rotation and the ankle fixation pad approximately two centimetres superior to the lateral malleolus. The subject was instructed to place their non-testing limb behind the counterforce pad and to use the handles on both sides for each trial. Each testing angle (60º for protocol 4 - Figure 13.c and 90º for protocol 5 - not shown) was confirmed with goniometric measurement to account for tissue and padding deformation[256]. Prior to any testing trials, the subject completed practice trials at each respective joint angle, which included verbal instructions about the

Figure 13: Example of testing layouts, constraints and orientations. Figure 13.a (left) shows the setup for the constrained movement measured with the load cell. Figure 13.b (center) shows the unconstrained load cell setup specifically at 60º (also collected at 90º). Figure 13.c (right) shows the constrained setup for the HUMAC NORM setup.

procedure and visual education about the pretension position on the computer monitor.

Collection Protocol

Each subject warmed up by cycling at low to moderate resistance using a self-selected pace for three to five minutes. Each subject was briefed on the testing procedures, including the goals and intentions of the tests, and given a walkthrough of the visual feedback system on the computer monitor. Familiarization occurred at every session using protocol 1, regardless of the randomized testing order, and included a series of progressive, ascending force output isometric knee extension trials, which culminated with at least one trial at maximal effort. Each subject was given verbal and visual feedback on performance. As part of the familiarization and practice trials, specific instruction and verbal cueing was explained and used. The term 'fast' in "fast and hard" was consistently emphasized throughout testing, which is necessary when collecting RFD and IMP metrics as opposed to PF[156]. Familiarization was followed by a five-minute rest, and each subject was given strong verbal encouragement throughout each trial.

The protocol and leg order was randomized and each subject completed three testing trials for each protocol. Testing was completed bilaterally, in alternating fashion, for every subject. Due to the brief contraction durations, rest between repetitions was set from 10 to 30 seconds in accordance with previous protocols[222]. The output was visually inspected for large deviations in force production (>250 N from prior trials), notable countermovement in the output, or any inconsistencies in the pretension state and removed if required. These false trials were repeated by the subject before progressing.

For each protocol the subject was allowed up to five practice trials per limb. For testing trials, the subject was told to achieve the determined pretension state by slowly extending the knee into the strap while observing the force line on the monitor. Once the force curve was at the pretension threshold for two seconds, the primary investigator would begin a countdown of "3-2-1-Go-Go-Go-Go-Go-Stop". The subject was instructed to begin the MVIC at any point after "1" and maintain the contraction until told to "stop".

Data Processing

Unfiltered load cell force-time data was saved directly in CSV format. The data was then imported and analyzed in MATLAB (MathWorks, Natick, MA), using a custom algorithm. The onset of force was defined as an increase in force that was greater than three standard deviations (3 SD) of force calculated from the 350 ms pretension window within one second before the contraction[1,71,72,253]. A modified version of this method was used; where the onset of force was calculated as the first 3 SD threshold crossing from the location of peak force working backwards. Time series outputs were visually assessed for outliers, which were removed from the analysis. PF was determined as the absolute maximum force recorded

during the entirety of the two-second contraction; and 20% and 80% of this PF were calculated. All further variables of interest were then determined from within the time interval created by the 20%-80% peak force thresholds ($time_{2080}$), as described by Cobian et al. and Dudley-Javoroski et al.[232,233]. RFD_{2080} was the average slope over the epoch (F/t) and impulse (IMP_{2080}) was the integral of the force-time curve during $time_{2080}$. PRFD was calculated using a 10 Hz 4th order low-pass Butterworth filter. Trials were removed from the analysis for the following reasons: if participants produced a significantly submaximal force onset rate (trials = 3, n = 2); if there was no steady pre-tension period (trials = 19, n = 9); and, if a dip in force was detected prior to onset (trials = 3, n = 2).

Statistical Analysis

All statistical analysis was conducted using RStudio IDE (Version 1.4.869, 2009 – 2020 RStudio, PBS). The statistical analysis explored the validity of the load cell protocols as compared to the isokinetic dynamometer. Each subject's trials for each protocol were averaged for further analysis. Further, if the subject did not participate in all protocols, they were also removed from all analysis (n = 19). Normality of averaged values was confirmed using Shapiro Wilks test for each protocol. Outlier analysis was conducted using intrasession, intra-subject z-scores. Any values greater than 3SD were removed from the analysis.

A two-way repeated measures ANOVA was conducted to determine whether there was a significant interaction between gender and layout on the kinetic variables. A one-way repeated measures ANOVA was used to compare 90° protocols (protocol 1 vs. protocol 3 vs. protocol 5). Normality was confirmed using Shapiro Wilks test and visually assess with Q-Q plots; assumption of sphericity was checked using Mauchly's test of sphericity. Post hoc pairwise comparisons with Bonferroni adjustment were calculated. In addition, Bland-Altman analyses with 95% confidence intervals (CI) were used to further relate the difference between paired kinetic variables to the mean of the pair across different protocols. All statistical significance was established a priori at $p<0.05$.

Results

There was no significant effect of gender on any kinetic variable with each device measurement for any of protocols, thus for all analysis, males and females were combined. In regards to protocols 2 and 4, the data for this study was collected as part of a larger data collection. From previous analyses it was found that the 90^{o} knee flexion angle trials had higher reliability than their 60^{o} counterparts, thus, validation results are provided for the 90^{o} trials only.

Mean and standard deviation (SD) can be observed in Table 7. All variables demonstrated slightly higher mean and SD values with protocol 5 (although not statistically significant), the constrained protocol, versus either protocol 1 or 3. No visible trend was apparent between the mean and SD with protocol 1 and 3. The standard error with 95% CI are also reported in Table 7

Table 7: Mean and standard deviation for each kinetic variable on each protocol with standard error and 95% confidence interval

Output	Mean ± SD			Standard Error [95% CI]	
	(P1) Load Cell/Constrained	(P3) Load Cell/Unconstrained	(P5) IsoK Dynamometer/Constrained	P1 vs. P5	P1 vs. P3
PF (N)	555 ± 132	537 ± 117	565 ± 142	52.0	47.3
				[-81.3, 103]	[-102, 66.0]
PRFD (N/s)	3454 ± 1265	3327 ± 1191	3676 ± 1572	539	464
				[-733, 1178]	[-950, 696]
RFD2080 (N/s)	2229 ± 602	2350 ± 878	2409 ± 1046	323	285
				[-391, 752]	[-382, 625]
IMP2080 (N/s)	33.5 ± 11.8	30.3 ± 10.3	33.2 ± 13.3	4.76	4.18
				[-8.72, 8.13]	[-10.6, 4.20]

PF = peak force; PRFD = peak rate of force development; RFD = rate of force development; IMP = impulse

Figures 14-17 represent ANOVA box and whisker plots for each kinetic variable collected with each protocol. A repeated ANOVA statistic was used to compare each kinetic variable between each protocol, and Figures 14-17 present graphical representation of the spread, median, and quartiles for each protocol.

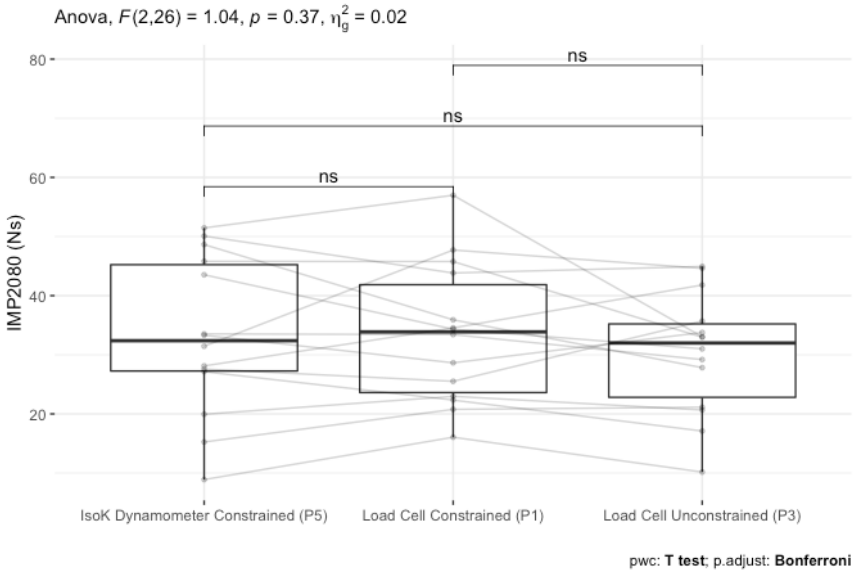

Figure 14: Repeated measures ANOVA: box and whisker plot IMP_{2080} (Ns); Abbreviations: Impulse2080 (IMP_{2080}) for protocols (P) 5, 3, and 1. Impulse = IMP; Newton.seconds = Ns; ns = Non-significant

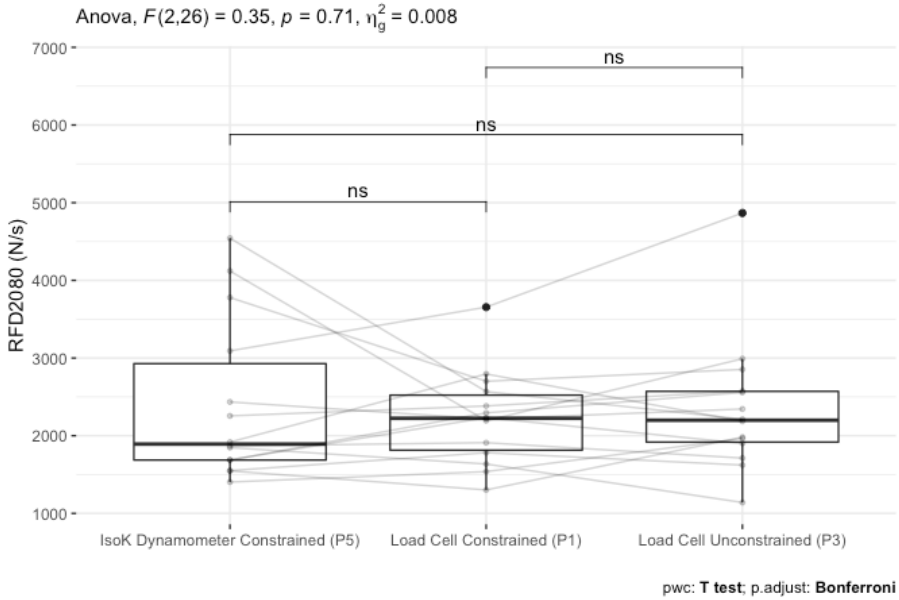

Figure 15: Repeated measures ANOVA: box and whisker plot RFD_{2080} (N/s); Abbreviations: Rate of Force Development2080 (RFD_{2080}) for protocols (P) 5, 3, and 1; Newton/seconds = N/s; ns = Non-significant

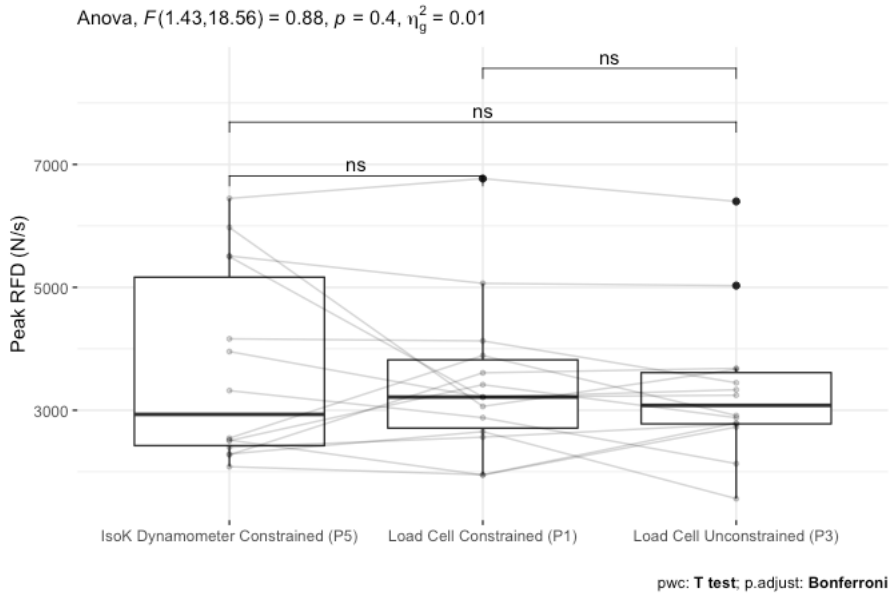

Figure 16: Repeated measures ANOVA: box and whisker plot PRFD (N/s); Abbreviations: Peak Rate of Force Development (PRFD) for protocols (P) 5, 3, and 1; Newton/seconds = N/s; ns = Non-significant

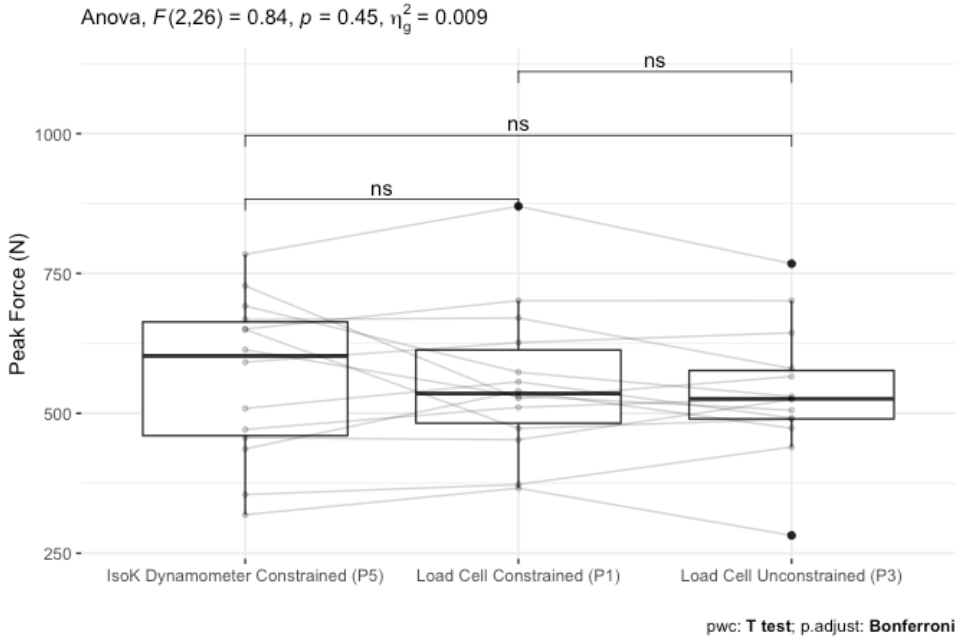

Figure 17: Repeated measures ANOVA: box and whisker plot PF (N); Abbreviations: Peak Force (PF) for protocols (P) 5, 3, and 1; Newtons = N; ns = Non-significant

For each variable no significant differences were found between protocols, although, as discussed in Figure 1, differences were visualized in regards to spread of data, medians, and quartiles. For all variables, protocol 5 produced larger spreads of data, producing larger upper and lower quartiles (especially in the cases of RFD_{2080}, PRFD, and PF). While, the medians for protocols 1 and 3 were very similar throughout all variables, protocol 5, again, deviated from the other protocols, producing slightly higher medians (Figure 17 - PF), and slightly lower medians (Figures 15 and 16 - RFD_{2080} and PRFD, respectively).

Discussion

The aim of this study was to investigate the use of a load cell as a clinically practical alternative to an isokinetic testing device in investigating knee extension kinetic variables. A novel approach to the analysis was implemented, focusing on using percentages of PF to create the data period to calculate the variables of interest across. This approach was implemented to represent a method by which automated data analysis could take place to show efficacy for implementation in a clinical setting. This methodology enabled the accurate capture of small epoch data, allowing for the calculation of explosive force variables, such as RFD, PFRD, and IMP.

To allow for the comparison between the constrained setup of the isokinetic dynamometer and the unconstrained load cell, a two-step process in the analysis was implemented. The initial analysis highlighted the differences in the measurement technologies by restricting the movement of the participant (constrained) in the isokinetic dynamometer chair whilst collecting data from trials with both devices. The secondary analysis was implemented to identify any differences between a constrained approach (representing a more laboratory organized procedure) and an unconstrained protocol (representing a more clinical procedure), while using the same technology (load cell) for both protocols.

The first step analysis investigated protocols 1 (isokinetic dynamometer/constrained) and 5 (Load cell/Constrained). “Constrained” was used to describe the participant set-up, being that each participant was seated on the isokinetic chair for data collection, which incorporated chest, trunk, and leg fixation (constrained protocol) for data collection. This first step compared the kinetic data collected in this constrained protocol using the isokinetic dynamometer (protocol 5) versus the load cell (protocol 1).

No significant differences ($p < 0.05$) were found between the two measurement devices across all four variables (PF, PRFD, RFD_{2080}, and IMP_{2080}) of interest. Although, no statistical significance was found between devices for the explored variables, small, consistent findings were observed with respect to mean

and standard deviation and interquartile ranges. For 3 of the 4 variables (PF, PRFD, RFD_{2080}) a slightly higher result in the mean (PF = 5% and PRFD 10% difference from protocol 3 to 2, and RFD = 8% difference from protocol 3 to 1) was noted for the isokinetic dynamometer when compared to the load cell. Also noteworthy was the greater variability (SD) for all four variables on the isokinetic dynamometer compared to the load cell. This could suggest a small sensitivity difference between the two devices. The authors speculate that the rigidity and constraint allowed the participants to produce more immediate and larger force on the isokinetic dynamometer, which explains the higher means, however the device itself (the padding specifically) also potentially lead to greater variability in performance and output. The plinth table was much less comfortable, being more rigid, and the kick strap was not padded to the degree of the isokinetic dynamometer.

The second step was designed to investigate the validity of the load cell used specifically in two different environments, Constrained (the isokinetic dynamometer chair with trunk fixation - protocol 1) and Unconstrained (a physiotherapy plinth without trunk fixation - protocol 3) both at 90 degrees of knee flexion. In exploring protocol 1 versus 3, as with the first step of this study, no significant differences were observed when using the load cell in a constrained protocol versus an unconstrained protocol for any of the 4 kinetic variables. Finally, Bland Altman plots were completed and explored, showing no significant increased or decreases in bias proportional to the mean of the values for all four variables.

The findings of this study confirm that the load cell device is a valid assessment tool for the quantification of PF, PRFD, RFD, and IMP, as the load reproduces results statistically similar to an isokinetic device. The load cell also performs similarly when used on a plinth compared to a more structured and constrained isokinetic chair. Finally, the unique method of identifying the testing window, created by percentages of peak force (20%-80%) may prove useful in the automation of data analysis, although more exploration of this method is warranted.

Limitations

This study is not without limitations. As reported by previous researchers[1,63,87], nuances, and limitations in the procedure of collecting RFD and other explosive force variables are difficult to fully eliminate. This study utilized a pretension state before the initiation of the force output. The ability to maintain a stable pretension state was difficult per reports from participants, and this could have impacted the force production capabilities. While this is known as a potential limitation, the study design and apparatus offered no plausible solution to this issue. Although differences between the constrained and unconstrained methods were part of the study design, padding, in the form of a folded towel, was required

on the plinth due to discomfort during maximal force events caused by sharp edges. This added padding would likely impact the results in a minor way, introducing a challenge in standardizing this methodology. Ultimately, a decision must be made to accommodate to either the rigidity of the system or the relative comfort of the testing subject.

Conclusion

The isokinetic dynamometer stands as the gold standard in the realm of force data capture in physical medicine. However, the cost and impracticality of the device often limits its use in clinical settings. It appears from our results that the load cell device can be used to produce valid strength and explosive strength measurements. More so, similar results can be obtained without extreme rigor and constraint, such as those seen with the isokinetic device. However, steps should be takes to minimize system laxity when possible and this will continue to improve the intersession variance found within other studies[62,253]. The overall findings of the study support the use of the load cell, in the aforementioned protocol, as a suitable alternative to the isokinetic dynamometry for the measurement of PF, PRFD, RFD, and IMP.

CHAPTER SIX – SUMMARY, PRACTICAL APPLICATIONS, RECOMMENDATIONS, CONCLUSIONS

Summary

The overarching question that guided the direction of the thesis was: can a load cell device be used to collect kinetic data, as a clinical diagnostic tool, for the assessment of knee extension force output in a rehabilitation setting? These kinetic data are valuable indications of an individual's force production capacity and can be extremely important in the profiling of performance, recovery, or potential risk[1,63,87]. While the breadth of research is not entirely conclusive about the use of these variables, the collection procedure and practicality remain large issues, involving the entire process, from equipment through to methodology and into analysis[1,8,32,63,87,202,207]. Therefore, this thesis intended to address these issues specifically with the practicing clinician in mind. This included the use of a load cell device (both a financially and practically more feasible option for clinical kinetic data collection), exploration of various protocol positions (incorporating varying degrees of system rigidity and constraint intended to simulate situations which may not be available in some testing environments), and utilized a data analysis process which both simplified the amount of kinetic variables recorder and was highly automated (requiring no additional manual selection or computation). PF was explored first in order to evaluate the consistency of the unique procedural methods of data analysis, largely based on the sample window generation using the SD onset of contraction method (defined by using 3 SD and working backwards from the data) combined with the 20%-80% of the peak force (the peak force value calculated within two seconds from the onset of contraction). As this combined method was novel, the first priority was to assess the variation in both the PF value and time duration that would be produced by this unique method, both of which impact Peak RFD, RFD_{2080}, IMP_{2080}). This was completed for all studies. This thesis is composed of three independent studies, by which the intrasession reliability, intersession reliability, and validity are evaluated according to the aforementioned constraints and criteria. This research provides valuable information regarding the scientific use of kinetic characteristics in physical medicine and performance.

A variety of kinetic variables, including RFD and IMP, within an isometric knee extension across three different protocols, intending to represent various degrees of subject constraint were investigated. The hypotheses of study 1 and study 2 were that the load cell device would be reliable (intrasession and intersession) in the measurement of all variables, to an acceptable degree. This hypothesis was not found to be true in its entirety. PF was notably more consistent across testing sessions, regardless of the measurement device or protocol. However, the remaining kinetic variables, RFD_{2080}, PRFD, and IMP_{2080},

demonstrated moderate to low consistency and therefore cannot be recommended for clinical use in a test-retest environment. This suggests that further investigations into standardizing the data collection protocols and providing sufficient familiarization is required. For the purposes of intrasession testing, the use of a plinth-based testing protocol for kinetic variables can be used confidently as the between trial reliability was acceptable.

The hypothesis of Study 3 was that there would be no difference in the kinetic data collected by the load cell device versus those same variables collected on a highly constrained, gold standard, dynamometer device, the isokinetic dynamometer. This proved to be true. The use of the load cell device, in an unconstrained environment (such as the physio plinth) can provide statistically similar results with kinetic data to that of a highly organized, fixed, dynamometer (isokinetic dynamometer). It is the hope that these findings encourage further research and increased clinical utility for the purposes of improving physical medicine and performance testing protocols.

Practical Application

With respect to the testing protocols, specifically in relation to the amount of constraint, the results of this thesis support the use of a load cell device for the purposes of explosive force profiling and other kinetic data in a knee extension testing environment. In support of previous literature[1,63,202], the load cell device, when compared to a gold standard dynamometer (isokinetic dynamometer), was found to be valid with respect to the variables described in these studies, except for the variable of PRFD. While the load cell device used on the isokinetic dynamometer chair was slightly more closely related to the isokinetic dynamometer data than those data from the plinth and load cell, these outputs were well within acceptable values. Therefore, based on the findings of this thesis, the load cell can be used in a clinical environment (without extreme fixation or constraint) to produce or profile kinetic data in knee extension contractions.

The methods described in these studies, especially in relation to the onset of contraction and testing window, provide a novel protocol by which RFD, IMP, and other kinetic variables may be used in a clinical setting with statistical consistency. Although this approach has the potential to be put into practice as it currently stands, several considerations need to be given to aspects of the data analysis process.

Firstly, the protocols presented in this thesis extend from existing methodologies presented in the literature in a manner that excludes the early phase of the subject trial. The early phase is often attributed as the most sensitive and representative of the neurologic aspects of explosive force, this initial (0-50 ms window) is inherently valuable[1,8,87,202]. However, the early phases are also the most inconsistently

reported time windows with respect to RFD characteristics, being attributed to a variety of procedural, individual, and technological factors[1,63,202]. From a clinical standpoint, early epoch data may be too volatile for "real" value to be placed on the results. Therefore, the methodology presented in this thesis may offer a more useful, and more consistent protocol for clinicians to use.

Secondly, the presented method necessitates the ability to produce maximal force in each trial. This may be difficult, or impractical, for individuals experiencing pain or at points of their rehabilitation which require a governed force output due to the healing or damaged tissue(s).

Recommendations

Collection of kinetic data, especially those using small epochs, can be quite variable, which necessitates a very structured methodology and appropriate set-up[1,8,87,202] This involves the management of certain aspects such as instruction, cueing, education, participation focus, and monitoring of the data. A variety of previously published research presented the sensitivity of RFD, and other explosive kinetic data, to subtle nuances within the testing environment[1,8,87,202]. This most certainly held true for this data as well. Testing trials must be closely monitored and subjects must be focused throughout the process. Any loss of focus, any discomfort, or any modification to their movement will yield significantly varied data and thus inconsistent outcomes. With this is mind, the tester should always educate and clearly explain the testing processes, give the subjects practice trials, and encourage the participant using consistent verbiage.

Additionally, the devices used for this thesis were all verified to collect at the same, high, sampling rate for explosive force variables (RFD). This is not guaranteed for all devices and can be a limitation to the use and generalization to other devices. Based on prior research, the lower thresholds of sampling for RFD are around 500 Hz, although it is encouraged that the frequency be closer to 1000 Hz if possible[1,63,202]. Changes in sample frequencies can produce unintended variances in data, and this should be considered when collecting data during small epochs.

The kinetic variables reported in this study provided a more simplistic version to profile various components of explosive force in an isometric contraction. As compared to previously reported RFD methodologies which have broken the force trial into a variety of arbitrary epochs, the methodology described in this thesis potentially offers a more usable and consistent version for future use. While the granularity of specific millisecond intervals (such as 0-50 ms or 50-100 ms) is lost in this method, these data may provide better retest properties and therefore be of more value in outcome-based programs.

When testing in a clinical setting, the 90° knee flexion position proved more consistent, and more reliable, than the 60° position. While this may be due to a myriad of factors, it is recommended that testing be completed at 90° for future studies and clinical assessment should recognize the higher variability when using this position. Finally, it is recommended that these metrics be explored further in future studies in an attempt to simplify the process of RFD and ultimately create a more homogeneous data pool in an effort to better understand explosive force as a metric of performance, recovery, or risk.

Conclusion

This thesis has discussed the long-standing history of muscle performance in science, specifically in the realm of physical medicine, which began by using manual, largely subjective, based assessments in order to gain better perspective on risk, performance, and outcomes. The process of muscle/tissue assessment remains a hallmark of physical medicine, and the last twenty years have seen substantial emphasis placed on the evolution in techniques and technology. However, modern physical medicine has been slow to evolve in practice and procedure, largely due to the lack of availability of affordable, clinically practical equipment, and the advanced understanding of muscle testing and tissue physiology. Fortunately, in terms of both physiological and technological utility, there has been substantial interest and investment into exploring the underlying mechanisms within a variety of musculoskeletal and neuromuscular processes.

This has culminated in a sizable number of educational resources and research publications justifying a deeper look into the capacity of basic muscle force characteristics. Muscle force characteristics employ a myriad of factors, ranging from peak muscular force, maximal strength or power, to joint specific force capacities and rapid force profiles. Peak force and maximal strength are certainly more popular muscular characteristics, but interesting evidence has emerged in support of rapid, or explosive, force characteristics due to their involvement within many daily tasks, such as balance and falls, and other performance determinants, such as performance ability[1,8,87,202]. This data has come to be generalized as RFD, which represent the capacity by which a muscle, or groups of muscles, can generate force within very short epochs. Subsequently, this has culminated in a focus on methodologies by which to collect and analyse this type of data, requiring technology that can record very precisely at high frequencies. These devices are often expensive, non-portable, and impractical for clinicians, ultimately limiting its utility as a major component in medicine and performance settings. The primary intention of this research was to explore a more practical device, the load cell, as a more viable option for clinical data collection. We have proven it's validity, however, our procedures need refining so as measures such as RFD, PRFD and IMP can be quantified more reliably.

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APPENDICES

Appendix 1. Abstract - Study 1

Introduction: Explosive force variables, such as rate of force development (RFD) and impulse (IMP), could be useful in determining risk or recovery status after an injury. However, RFD and IMP are relatively unused within the rehabilitation and performance community. A major reason for this is the availability, practicality and affordability of clinical tools (isokinetic dynamometers) that can collect this type of data. Thus, this study explored the intrasession reliability of these kinetic variables collected using a load cell device as an alternative for clinical use.

Methods: Thirty-two healthy volunteers (14 males and 18 females: age 31.8 ± 7.91 years) completed three rapid maximal-effort, isometric, knee extensions to determine the intrasession reliability of kinetic variables collected via a load-cell device within three testing protocols varying in constraint and knee position.

Results: Intrasession reliability was found to be the highest with Peak Force (PF) (ICC = 0.97 to 0.99; CV = 3.20%-4.50%), for all protocols. However, with respect to RFD_{2080} and IMP_{2080}, protocol 1 demonstrated the highest ICC and lowest CV%: (RFD2080: ICC = 0.82 to 0.86; CV = 10.5%-11.8%) and (IMP_{2080}: ICC = 0.91 to 0.93; CV = 11.4%-12.6%) Values were similar for the two knee positions, with slightly higher reliability was found for the 90 degree position compared to the 60 degree knee position. The physiotherapy plinth (unconstrained protocol) achieved comparable reliability with the isokinetic chair (constrained protocol) for peak rate of force development (PRFD) and IMP_{2080} in the 90 degree knee angle.

Conclusions: Measures of PF and PRFD collected using a load cell during knee extension were found to have acceptable intersession reliability. However, results are not interchangeable with the gold-standard dynamometer protocol. Practitioners should also be aware that the reliability of most RFD_{2080} and IMP_{2080} epochs were questionable. Future research should examine assessment at longer muscle lengths as these may result in improved reliability.

Appendix 2. Abstract - Study 2

Introduction: Explosive force variables, such as rate of force development (RFD) and impulse (IMP), could be useful in determining risk or recovery status after an injury. However, RFD and IMP are relatively unused within the rehabilitation and performance community. A major reason for this is the availability, practicality and affordability of clinical tools that can collect this type of data. Thus, this study evaluates the reliability (coefficient of variation – CV; intraclass correlation coefficients – ICC) of kinetic variables recorded using a load cell device.

Methods: 12 healthy subjects (6 male and 6 females; age 31.0±6.40 years) completed 3 maximal knee extension isometric contractions for 3 separate testing protocols, over three testing sessions, separated by 7-10 days. Peak force (PF), Rate of Force Development (RFD), Peak Rate of Force Development (PRFD), and Impulse (IMP) measures were used for analysis. Protocols varied in knee flexion angle and degree of rigidity or fixation.

Results: PF was the only variable to have small variability (CV < 10%; ICC > 0.67) across all three protocols. Lower variability was associated with the isokinetic protocols when measuring RFD however, better consistency was observed for the PF and Imp_{2080} measures with the plinth layout (unconstrained).

Conclusions: Practitioners can have confidence when evaluating knee extension PF using load cell technology. For RFD, it is recommended a more constrained approach is used. It would seem that most protocols/variables would benefit from additional familiarization.

Appendix 3. Abstract - Study 3

Introduction: Kinetic data collected in short time intervals such as rate of force development (RFD) and impulse (IMP) offer unique insight into force generation characteristics. These data often require specialized technology by which force can be measured in extremely small epochs, and under constrained environments. This data is increasingly valuable in physical medicine; however, the practicality of commonly used collection devices is a major issue for clinical use and integration. Therefore, this study explored the validity and reliability of a load cell device when compared to an Isokinetic dynamometer device using a novel approach to data analysis.

Methods: 26 healthy subjects (12 male and 14 female, age 32.0±8.90 years) completed three maximal, explosive, knee extension isometric contractions to compare a variety of kinetic force variables (peak force (PF), peak rate of force development (PRFD), RFD_{2080}, and IMP_{2080} between devices. Assessments were completed across the two devices with varying degrees of system rigidity and fixation, including a load cell and an isokinetic dynamometer. Additionally, contractions were performed at 90° of knee flexion.

Results: Small observable differences were noted in mean and standard deviation across kinetic variables; however, no significant differences ($p >= 0.05$) were found between devices for the 90° knee position

Conclusions: Based on these findings, evaluating explosive force data with a load cell is not different than those collected on the Isokinetic dynamometer, and may serve as a more practical and cost-effective alternative.

Appendix 4. Subjective Information Sheet

Participant Information Sheet

Date Information Sheet Produced: 6 December 2019

Project Title

Assessment of Kinetic Variables in Knee Extension Using Load Cell Technology in a Healthy Population: Reliability and Limb Asymmetry.

An Invitation

Hello. My name is Chris Juneau and I am completing a Masters in Philosophy with AUT. You are invited to take part in the above-mentioned research project. Your participation in this research is voluntary. You are free to withdraw consent and discontinue participation from the study at any time without influencing any present and/or future involvement with the Auckland University of Technology.

Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of this Research?

The purpose of the study is to investigate the use of a load cell, or strain gauge apparatus, in measuring types of force in a knee extension contraction. Particularly, we will be looking at rate of force, or how much force can be produced over a specific amount of time. The intention of this research is to provide new, and more practical, tools for measurement and assessment of force in performance and rehabilitation settings. I will be happy to discuss aspects of this research in further detail.

How was I chosen to be asked to participate in the Research?

You were chosen to participate in the study as you meet the follow criteria: Are a healthy individual, between the ages of 18-45, Do not have any significant knee medical injury history, Are able to perform a maximal knee extension movement. This is a randomly sampled group of participants in the community, discovered by word of mouth and information flyers. You will then contact the primary researchers to discuss the study and organize testing dates, should you decide to take part in the study. This will involve the primary research sending you a consent document, which will be reviewed prior to your enrolment in order to prevent any confusion.

How do I agree to participate in this Research?

Your participation in this research is voluntary (i.e. it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. Your participation will involve an initial phone conversation about the study and to answer any questions you might have. You will then attend a practice session, which includes information for you to read and sign, and some practice exercise. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What happens in this Research?

If you agree to participate, your invovlement will involve 2 to 3 total sessions, depending on the group you are selected to. You will have the option to deny participation at any time.

If you choose to enroll in the study, you will be asked to complete a health questionnaire that will be recorded and used as part of the analysis of the data obtained. This history will be recorded in a database only accessable to the investigators directly involved in the study.

All sessions will take roughly 1 hour to complete.

- Session 1: Familiarization
  - This involves information about current measures of height, weight, some general information about your health, and some speciifc information regarding your knees.
  - You will complete a small warm-up and complete a series of practice trials on the testing apparatuses.
    - This will involve a mild warmup on a bike followed by a series of knee extensino contractions into a strap. These will be a series of 10 maximal contractions on each leg.
- Session 2 & 3 (if necessary): Testing Sessions
  - You will complete a small warm-up and complete a series of practice trials on the testing apparatuses.

- You will be asked to sit on the edge of a table, and a strap attached to your lower leg, just above your ankle. This strap will not allow your leg to move throughout the trials. You leg will be place at 2 positions for 5 trials each, equaling 10 total contractions per leg. This protocol will happen on both legs.

If you choose to enroll in the study, which is voluntary, you may be randomly assigned to one, of two groups, as part of the study. Depending on the group, you may be asked to return in 1 week, 7 days, to repeated the testing protocol.

If at any point, you experience any pain, discomfort, or unwillingness to produce a maximal contraction, you will be removed from the study.

This study will be completed at Auckland University of Technology's campus at the Millenium facilty.

WHAT ARE THE DISCOMFORTS AND RISKS?

Risks are only those discomforts and risks that normally occur from participating in a typical maximal effort workout. You will complete a mild warmup and a series of maximal exertion, short interval, knee extension contractions on both legs.

WHAT ARE THE BENEFITS?

Partnership between participants and researchers will be an essential component of this study. Despite there being no direct benefits to the individual participants, the outcomes of this research will be used to further our understanding related to force in the knee. This research has the potential to improve assessment, management, and performance related to the knee. Practical, objective, data collection tools can improve the quality of injury risk assessment profiles and performance related interventions. Data from this study may be included in the researchers MSc thesis and published as a paper.

WHAT COMPENSATION IS AVAILABLE FOR INJURY OR NEGLIGENCE?

There is no compensation for this research, and you are undertaking the activity voluntarily. In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

Jung, S.-H., Kim, M.-H., Hwang, U.-J., Kim, J.-H., & Kwon, O.-Y. (2017). Comparison of Knee Extensor and Hip Extensor Strength According to Wall Squat Performance. *Physical*

There are appropriate first aid equipment / facilities and trained staff to manage any adverse events during testing.

HOW IS MY PRIVACY PROTECTED?

The data from the project will be coded and held anonymously in secure storage under the responsibility of the principal investigator of the study in accordance with the requirements of the New Zealand Privacy Act (1993). This information will be destroyed after 6 years, and will not require any action on your part in completing this task.

All reference to participants will be by code number only in terms of the research project and publications. Identification information will be stored on a separate file and computer from that containing the actual data. Only the investigators will have access to computerised data obtained from the participants.

WHAT ARE THE COSTS OF PARTICIPATING?

There is no additional costs involved with this research, all equipment is supplied.

OPPORTUNITY TO CONSIDER INVITATION

Please take the necessary time you need, up to a week, to consider the invitation to participate in this research. It is reiterated that your participation in this research is completely voluntary.

If you require further information about the research topic please feel free to contact Chris Juneau (details are at the bottom of this information sheet).

You may withdraw from the study at any time without there being any adverse consequences of any kind.

You may ask for a copy of your results at any time and you have the option of requesting a report of the research outcomes upon completion of the study.

How do I join the study?

If you are interested in participating in this research, please feel free to contact Chris Juneau (details are at the bottom of this information sheet).

Participant concerns

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Dr Jonathon Neville. Email: jono.neville@aut.ac.nz

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz, (09) 921 9999 ext. 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researchers Contact Details:

Chris Juneau, email: cmj027@yahoo.com, phone +64 (0)21 108 8707

Project Supervisor Contact Details

Dr. Jono Neville, Sports Performance Research Institute New Zealand, School of Sport and Recreation, Auckland University of Technology. Email: jono.neville@aut.ac.nz or phone +64 9 921 9999 ext. 7306.

Appendix 5. Consent Form

Consent to Participation in Research
Participant Consent Form

Title of Project: ***Assessment of Kinetic Variables in Knee Extension Using Load Cell Technology in a Healthy Population: Reliability and Limb Asymmetry.***

Project Supervisor: **Dr. Jono Neville, PhD**

Researchers: **Mr. Chris Juneau**

- I have read and understood the information provided about this research project in the Information Sheet dated 15th December 2019;
- I certify that I am in good health and able to participate in the isometric knee extension trials;
- I have had an opportunity to ask questions and to have them answered;
- I agree to participate in the research;
- I understand that taking part in this study is voluntary (my choice) and that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way;
- I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible;
- I consent to future use of this data. (Tick one) (note: this data will remain anonymous regardless of your selection)
  - Yes O No O
- I wish to receive a copy of the report from the research: (tick one): Yes O No O

Participant Signature: .....

Participant Name: .....

Date: .....

Project Supervisor Contact Details:

Dr. Jono Neville, PhD
Sports Performance Research Institute New Zealand (SPRINZ)
School of Sport and Recreation
Auckland University of Technology
Private Bag 92006
Auckland 1020
64 9 921 9999 ext 7306
jono.neville@aut.ac.nz

Appendix 6. Health Questionnaire

2019 PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1) Has your doctor ever said that you have a heart condition ☐ OR high blood pressure ☐?	☐	☐
2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** _____	☐	☐
6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it **does not limit your current ability** to be physically active. **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
7) Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.
Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow International Physical Activity Guidelines for your age (www.who.int/dietphysicalactivity/en/).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

PARTICIPANT DECLARATION
If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for its records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME _____ DATE _____

SIGNATURE _____ WITNESS _____

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER _____

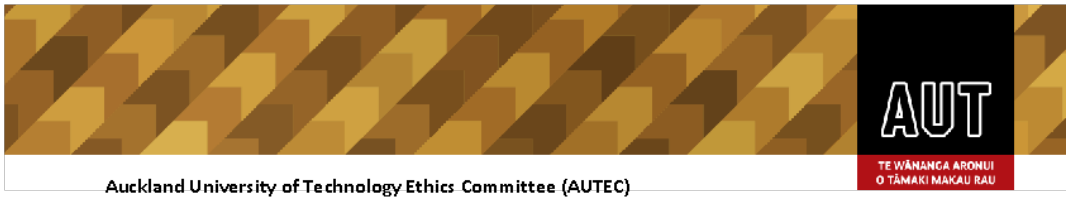
If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at **www.eparmedx.com** before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity program.

 1 / 4
11-01-2018

Appendix 7. Ethics Approval



Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

17 December 2019

Jonathon Neville
Faculty of Health and Environmental Sciences

Dear Jonathon

Re Ethics Application: 19/447 Assessment of kinetic variables I knee extensions using load cell technology in a healthy population: Reliability and limb asymmetry

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 17 December 2022.

Non-Standard Conditions of Approval

1. In the section 'how was I chosen' remove the reference to confusion by changing the last bit of the last sentence to read '...enrolment so you understand what is involved'.
2. Be specific about the future use of data by rewording the last paragraph on privacy to read 'Data will be stored for 6 years in the SPRINZ research database in a de identified form, and may be used for future research and shared with SPRINZ approved researchers.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. 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.
7. 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.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted. When the research is undertaken outside New Zealand, you need to meet all ethical, legal, and locality obligations or requirements for those jurisdictions.

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

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

Yours sincerely,

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

Cc: sdn1317@autuni.ac.nz