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Biomechanical assessment and determinants of punching in boxers

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PhD

A thesis submitted to Auckland University of Technology in fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

2018

School of Sport and Recreation

Abstract

Punching is a fundamental human movement that is the defining action of many combat sports, most of all boxing where it is the primary method of attack. This thesis investigated the biomechanics and determinants of punching to answer the question, “What defines effective punching in boxing?” The first chapter of the thesis expanded on these themes, as well as identifies current gaps in the literature relating to the analysis of punching in boxing. Chapter two was a narrative review of methods used to assess impact kinetics and the contributors to impact kinetics in combat sports. The third chapter was a narrative review on effective mass, an impact variable of interest in the literature. The chapter focused on defining the variable and the methods proposed to maximise effective mass. The review found that effective mass was the inertial contribution of a fighter to impact. Additionally, the review found that double peak muscle activation is currently the only process proposed in the literature to increase effective mass. There is a potential gap in the literature regarding continued force application by the lower body during impact. Chapter four, a qualitative study of experienced boxing coaches exploring their views on effective punching performance. The results of the study are in agreement with Chapter two in that the lower body’s contribution was key to producing an effective punch. Chapter five presents an original method to measure impact kinetics using practical, simple, affordable, and relevant equipment. Reliability test statistics determined that all measures had acceptable reliability (CV $\leq$ 4.6%). Validity was determined via linear regression of a spectrum of loads and coefficient of determination. All variables were found to have a good fit to the model ($r^2 \geq 0.92$) except for rate of force development ($r^2 \geq 0.57$). Chapter six, assessed the reliability of the method described in Chapter five on a cohort of experienced boxers and untrained participants tested intra and intersession. Reliability statistics were small (ICC < 0.67 and CV < 10%) to moderate (ICC < 0.67 or CV < 10%) and technical error of measurement was moderate (TEM = 0.60 – 1.19). Chapter seven was a mixed method analysis of ground reaction forces, electromyography, and high-speed video to define the phases of straight and hook punches. The definition of phases was a novel contribution to the punching literature, identifying three phases for straight punches (initiation, execution, and impact) and four for hook punches

(wind-up, initiation, execution and impact). The chapter used qualitative and quantitative methods to discover the uniqueness of each punch type and the differences between lead and rear hand punches of the same punch type. Chapter eight, the final experimental study of the thesis, used the findings from throughout this research to identify the determinants of impact kinetics in straight and hook punches. Findings from the study further reinforce the uniqueness of each punch type as no individual variable determined impact kinetics across them. There were general commonalities, as the majority of determinants were found in the lower body (19 of the 28), confirming the findings of Chapter Two, and those related to the upper body indicated that relaxation of the musculature was key to optimising impact kinetics. Results relating to effective mass found that double peak muscle activation had no correlation, while the lower body had meaningful correlations. This finding confirms the theory introduced in Chapter Three regarding the lower body's continued force application during impact, but conflicts with current theories relating to double peak muscle activation. The final chapter (nine) is a summary of findings, areas for future research, and practical applications. This PhD has contributed knowledge regarding the understanding of effective mass in punching, the role of ground reaction forces as a key to punching, the kinematic and kinetic events of punching in a phase model, and the determinants of impact kinetics in straight and hook punching.

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Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except 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.

Chapters two through eight of this thesis represent seven separate papers that have either been published, have been submitted, or will be submitted to peer-reviewed journals for publication. My contribution to these works, and that of the various co-authors, are outlined on the following pages and have been approved the inclusion of the joint work in the body of this masters' thesis.

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Date January 1, 2018 ……………………………………

Candidate contributions to co-authored publications

Chapter 2. Lenetsky, S., Harris, N., & Brughelli, M. (2013). Assessment and contributors of punching forces in combat sports athletes: Implications for strength and conditioning. *Strength & Conditioning Journal*, *35*(2), 1-7.	Lenetsky, S. (90%) Harris, N. (5%) Brughelli, M. (5%)
Chapter 3. Lenetsky, S., Nates, R. J., Brughelli, M., & Harris, N. K. (2015). Is effective mass in combat sports punching above its weight?. *Human movement science*, *40*, 89-97.	Lenetsky, S (85%) Nates, R.J. (5%) Harris, N.K. (5%) Brughelli, M. (5%)
Chapter 4. Lenetsky, S., & Lindsay, R. (2017). Coaching Boxing: An expert analysis of punching performance in boxers. *Qualitative Research in Sport, Exercise and Health*, In prep.	Lenetsky, S (90%) Lindsay, R. (10%)
Chapter 5. Lenetsky, S., Nates, R.J., Brughelli, M., & Schoustra, A. (2017). A practical method for the measurement of striking impact kinetics via accelerometery and inertial modelling. *Journal of Sport Science*, In prep.	Lenetsky, S (80%) Nates, R.J. (10%) Brughelli, M. (5%) Schoustra, A. (5%)
Chapter 6. Lenetsky, S., Brughelli, M., Nates, R.J., Cross, M.R., & Lormier, A.V. (2018). Variability and reliability of punching impact kinetics in untrained participants and experienced boxers. *Journal of Strength and Conditioning Research*, 32(7), 1838-1842.	Lenetsky, S. (80%) Brughelli, M. (5%) Nates, R.J. (5%) Cross, M.R. (5%) Lormier, A.V. (5%)
Chapter 7. Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Defining the phases of boxing punches: A mixed method approach. *Journal of Strength and Conditioning Research*, In press.	Lenetsky, S. (80%) Brughelli, M. (5%) Nates, R.J. (5%) Neville, J.G. (5%) Cross, M.R. (2.5%) Lormier, A.V. (2.5%)
Chapter 8a. Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Ground reaction force determinants of punching impact kinetics in male boxers. *International Journal of Sports Physiology and Performance*, In prep. **Chapter 8b.** Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Electromyographic determinants of punching impact kinetics in male boxers. *Scandinavian Journal of Medicine & Science in Sport*, In prep.	Lenetsky, S. (80%) Brughelli, M. (5%) Nates, R.J. (5%) Neville, J.G. (5%) Cross, M.R. (2.5%) Lormier, A.V. (2.5%)

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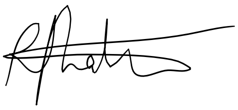

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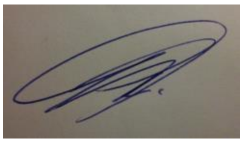

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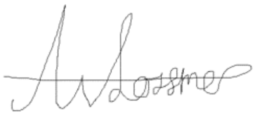


Anna V. Lormier

Acknowledgements

A thesis has been written! I would write, “I wrote a thesis!”, but that wouldn’t be totally true. This thesis is the work of hundreds of people, many who don’t even know they were involved. People who allowed me to get to the place where I could perform this research and write this manuscript. There are people who supported me in innumerable ways during the process providing me with kind words, guidance, and perspective. Those who’s shoulders I have stood on, who’s works allowed me to do mine. To all of those that helped me make this a reality, thank you.

To my primary supervisor, **Matt Brughelli**, my mentor, friend, and colleague. We have both been through a lot during this process, both good and bad, growing as people together. Your guidance, understanding, and openness to my crazy ideas was invaluable. I don’t think we had the typical supervisor/student relationship, and for that I am glad. Thank you, brother.

Roy Nates, my secondary supervisor and strange South African clone of my dad. Your tenacity and pragmatic view gave me the direction I needed to complete my PhD. I know the day I supervise my first thesis I will quote you unendingly. “This is just a PhD, you don’t have to answer everything. Get it done and then keep writing”, is the best piece of advice I have received in my academic career. Toda roba.

Nigel Harris, my tertiary advisor, I can say without a shadow of a doubt I would not be here without you. You have been the one constant in my academic life from the Diploma of Fitness Training to now. Thank you for seeing potential in me, nurturing my growth as an academic, and helping me to get to this point. In the end, I failed in following the advice you gave me after my first data collection in undergrad, “Never work with people or technology”, still, I think it all came out OK in the end.

Jono, Anna, Matt, and **Riki,** the co-authors, “lab assistants”, programmers, and the people in the trenches with me. You gave up amazing amounts of time to help me perform my data collection and analysis. Without you, what was an arduous journey would have been nearly impossible. Your incredible intellects made my job easier and taught me to be a better researcher along my journey. Thank you for taking this journey with me.

To my friends from AUT: **Matt, Scott, Riki,** and **Eric**. I've never been a guy with many friends in my life and the gift of being accepted into your group made me a better man. I will look back to our days together fondly for the rest of my life. From the first time I worked with each of you, your collective ability and professionalism astounded me. To see how far your careers and study have taken you warms my heart. Your quality as people is second to none, and your friendship, despite my failure to stay in contact, is a joy.

To my "adopted" parents, **Frank** and **Cindy**, I wouldn't have even made it out of high school without you. I was on a bad path until you let me glom onto your family. Your wisdom and love helped a stupid angry kid see a better path. Thank you for caring when you didn't have to, I love you guys.

To my real parents, **Mark** and **Holly**, thank you for providing me with the environment that made me who I am. Dad, your love of science, art, and literature was a gift. You are my hero, best friend, and favourite verbal sparring partner. Mom, every year that goes by I see how alike we are, your obsessive nature is my obsessive nature, we are both odd ducks born to be specialists. My speciality has taken me to a place far from your interest, but where ever I go, I take a part of you.

To my daughters, **Nila** and **Maddie**, thank you for patience in this process. I know you don't realise now the sacrifices you have made, but I do. I will make up for the time I have missed with you writing on nights and weekends I should have been with you two. I hope one day you read this and see the work that kept me away from you. I love you both with all my heart.

Donna, my wife, soul mate, and the best thing that ever happened to me. You above all others deserve credit for this thesis. You have supported my work financially, emotionally, and intellectually. Not only that, but you gave me two beautiful daughters during this process. You amaze me. You moved to New Zealand with me, supported my decision to study at university, put up with my workaholic years, faced your illness, raised our children, made another move to the States, and supported me through one of the hardest years of my life. I could thank you now until my last breath and it wouldn't be enough. I know I'm not the

easiest guy to deal with. I alienate people without even meaning to, but your ability to call me on my BS makes me love you more. Your love makes me want to be a better person, a person worthy to be your husband.

Ethical approval

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC; #12/332) originally on 18 January 2013, with minor amendments approved on 27 August 2015 (see Appendix 1).

List of common abbreviations

PF	Peak force (N)
MP	Mean force (N)
Fmax	Maximal force (N)
Fmean	Mean force (N)
EM	Effective mass (kg)
GRF	Ground reaction force (N)
RPE	Rate of perceived exertions
DPMA	Double peak muscle activation
LHH	Lead hand hook
RHH	Right hand hook
CV	Coefficient of variation
ICC	Intra-class coefficient

CHAPTER 1

INTRODUCTION AND RATIONALE

Background and importance

In 1961 the American writer Robert Ardrey published the book "African Genesis", popularising the concept of the killer ape (Ardrey, 1961). The killer ape theory proposed that the intrinsic aggressive and violent nature of human ancestors gave homo sapiens an evolutionary advantage over their ape cousins. The theory primarily focused on psychological and neurological aspects of humans and their ancestors, but did include evolutionary adaptations including upright posture (Ardrey, 1961). The proposed theory did face large amounts of criticism from the scientific community, most notably from the Spanish National Commission for the United Nations Educational, Scientific, and Cultural Organisation (UNESCO), who stated, "It is scientifically incorrect to say that war or any other violent behaviour is genetically programmed into our human nature" (*Seville Statement on Violence*, 1986).

In the last decade, works by David Carrier and Michael Morgan in the field of evolutionary biology have produced evidence supporting parts of the killer ape theory (Ardrey, 1961). Carrier and Morgan's work focused on physiological adaptations that evolved for person to person violence, specifically through upper limb strikes performed with a closed fist, i.e. punching. In Carrier's earlier work (Carrier, 2011), he establishes the importance of the upright bipedal posture in improving punching impact kinetics, finding 43.04 ± 9.00% greater impulse in a bipedal posture over a quadruped posture when punching. Furthermore, Carrier links the impact kinetic of the strikes thrown to the height of the attacker. This finding is theorised by Carrier to explain in part, the evolution of bipedalism in humans. Those that could stand upright would defeat those that couldn't and later those who were taller could defeat those that were shorter. Carrier cites sociological literature in defence of this theory, highlighting that modern humans prefer taller mates and that those of greater stature have more success in professional matters (Puts, 2010). In 2013 Morgan and Carrier produced a study exploring the protective buttressing of the human hand (Morgan & Carrier, 2013). The human hand differs from that of other great apes in the ability to form a closed fist that was theorised to protect the hand and provide improved force transmission during impact. The authors state that a closed fist punch more than doubled the ability to transmit punching forces over open hand strike. The unique structure of the hand to fully flex the digits gave an advantage in combat over other ancestral branches, potentially providing them with a way to develop tools while deciding combat for mates and resources in the interim.

As a result of the above evolutionary adaptations, Carrier and Morgan (2014) proposed that the human face developed buttressing to protect against impact. These buttressing features included a more orthognathic face, increased bone layers in the orbit, and larger muscles in the jaw and neck. This hypothesis differs from previous theories that proposed evolutionary changes to human facial structure was primarily due to dietary changes (Grine & Kay, 1988). These theories have been called into question with research into the diets of Australopithecus (a human relative) (Grine & Teaford, 2006). Carrier and Morgan's new hypothesis explains the human divergence from that of the other apes. The most recent work by Carrier and a colleague (Carrier & Cunningham, 2017), further supports the idea that much of human evolution was influenced by physical violence between human ancestors. The authors' conclusions regarding the foot posture of great apes and other primates indicated that a plantigrade foot position (digits and metatarsals placed on the ground) allowed for greater ground reaction forces (GRF), and thus greater impact kinetics during punching. The plantigrade posture was found exclusively in great apes and is theorised to have evolved in part due to sexual selection of the more physically dominant of the species. Combined, Carrier and Morgan's work highlight the action of punching as a fundamental human movement. This action has defined the human species, affecting the evolution of our hands, faces, feet, sexual attraction, and even our most defining human feature, bipedal posture. The theory of the violent ape remains a controversial one, but recent works do indicate that our bodies were shaped by violence, specifically through the act of punching.

In modern culture, inter-personal violence has become a social transgression (Elias, 1986; van Bottenburg & Heilbron, 2006). In the place of semi-random violence for social dominance and material gain, humanity has civilised inter-personal violence into combat sports (van Bottenburg & Heilbron, 2006). The process of civilising violence has been termed “sportification” (Elias, 1986), a gradual shift from single and group violence without organisation, into sports with structured rules, concepts of “fair play”, referees, and other trappings familiar with modern athletes and spectators (Elias, 1986). Among the western combat sports, boxing was one of the first to go through the sportification process.

Archaeological evidence of fist-fighting contests trace as far into the past as the 3rd millennium BCE (Olver et al., 2017). Although, it is unknown if rule systems existed in contests at that time. The earliest known sportified version of boxing came from ancient Greece, where it was first introduced as an Olympic event in 688 BCE. Practiced by the ancient Greeks for centuries, the Roman Empire’s ascendance in the region continued the popularity of the sport for centuries. With the fall of the Roman Empire, so too went organised boxing in the West. It wasn’t until the 17th century in London that boxing returned to historical record as an organised sport (Olver et al., 2017). Contested without gloves, bare knuckle boxing grew in popularity throughout the British Isles despite the semi-legal status (Olver et al., 2017). In 1838 boxing underwent a major change towards sportification with the creation of the London Prize Rules. This rule set limited wrestling during bouts (boxing competitions) and introduced the concept of rounds, i.e. periods of combat separated by rest. Under the London Prize Rules, a round ended on the downing of one of the contestants. With the introduction of this rule set, the popularity of boxing surged to new levels with trans-Atlantic rivalries developing between Britain and the United States. In 1867 boxing was refined again with the introduction of the Marquess of Queensberry rules. Now boxers were required to wear padded gloves, rounds were based off of a time period (3 minutes), wrestling was banned, and a downed boxer had 10 seconds to return to the bout before being ruled a knockout. Over the following century western boxing continued to change, weight classes were added, professional and amateur versions of the sport were developed, rules for boxer safety improved, and glove technology advanced. Despite these changes, at its core, boxing has remained fundamentally the same, a contest based on punching and the primer western combat sport (Olver et al., 2017).

Scientific literature exploring the defining action of boxing, (i.e. punching) is limited (Lenetsky, Harris, & Brughelli, 2013). However, comparison between punching in boxing and other combat sports is common (Lenetsky et al., 2013). As such, punching in combat sports in general will be explored in this introduction. Biomechanical literature on punching has been focused primarily on kinematics, muscular activation patterns, and kinetics. While limited, this research has laid a foundation for future study. Kinematic analysis of punching has explored joint velocities and angles (Cabral, Joao, Amado, & Veloso, 2010; Tong-Iam & Lawsirirat, 2016), trajectory differences based on punch types (Cheraghi, Alinejad, Arshi, & Shirzad, 2014; Whiting, Gregor, & Finerman, 1988), the effects of punches thrown in combination (Piorkowski, 2011), and the effects of experience on those factors (Whiting et al., 1988). These findings describe punching as an action characterised by high velocity rotation of the pelvis and torso. The literature identifies the differences in trajectory of hook and straight punches, in that hook punches take more total time to impact due to the arching nature of the punch. Results of Piorkowski (2011) establish the efficacy of multiple punches thrown in alternating rear and lead hand combinations, further reinforcing the importance of the rotary component of punching and clear relationships connect experience to improved technique in these tasks. These findings have served to describe the punching action, but provide little information into how combat sports athletes maximise rotation and the role of rotation on impact kinetics.

Research into muscle activation patterns during punching reported a unique sequence characterised by an activation, relaxation, and re-activation of the body's muscle groups throughout the action (McGill, Chaimberg, Frost, & Fenwick, 2010). Termed double peak muscle activation (DPMA) (McGill et al., 2010), this activation pattern is theorised to improve punching as the first muscular activation propels the fist towards a target, relaxation occurs to increase the punch velocity by reducing the inhibitory factors of force production in muscle (McGill et al., 2010), and a re-activation to stiffen the body and arm, potentially increasing force transition during impact (McGill et al., 2010). However, assessment of DPMA and force transmission simultaneously has not been reported. As such, much of the current literature relating to DPMA remains theoretical.

The literature regarding the kinetics of punching has focused on two primary aspects, the lower body's contribution to punching, and the kinetics of impact.

The exploration of the lower body's role in punching is heavily influenced by the 1983 work by Filimonov and colleagues, who first identified that the lower body's contribution (ground reaction forces) was linked to impact kinetics. Later works reinforced Filimonov et al.'s (1983) findings in Karateka (karate practitioners) (Cesari & Bertucco, 2008), and in the horizontal ground reaction forces produced during the punches of martial artists (Gulledge & Dapena, 2008). More recent works examining strength and power measures have found correlations with punching impact kinetics (Loturco, Artioli, Kobal, Gil, & Franchini, 2014; Loturco et al., 2015). These studies found that lower body power attributes have a greater correlation to impact kinetics than measures of the upper body. A thesis by Stanley (Stanley, 2014) explored the training of muscular power in boxers and found that increases in lower body power improved impact kinetics, further confirming Filimonov et al.'s (1983) conclusions. Although, direct relationships between lower body actions during the punch and resulting impact kinetics have not been explored in the literature.

Impact kinetics and the methods to assess them compose a substantial area of research in the punching related literature (Atha, Yeadon, Sandover, & Parsons, 1985; Fortin, Lamontagne, & Gadouas, 1995; Liu, Fujimoto, & Tanaka, 2014; J. D. Pierce, Reinbold, Lyngard, Goldman, & Pastore, 2006; Smith, Dyson, Hale, & Janaway, 2000; Walilko, Viano, & Bir, 2005). This focus has proven relevant due to the results of the boxing specific works of Smith et al. (2000) and Peirce et al. (2006) who found impact kinetics directly linked to experience levels and bout victory respectively. These studies place impact kinetics as a key determinant of boxing performance. Although, specific impact kinetic variables which are most effective in boxing currently have no evidential backing in the literature.

Early research on impact kinetics focused on peak and mean force results from punches (Atha et al., 1985; Girodet, Vaslin, Dabonneville, & & Lacouture, 2005; Pierce et al., 2006; Walilko et al., 2005). The reasoning behind this focus is unclear, but the findings of Smith et al. (2000) and Peirce et al (2006), did use these variables in their research. More recently, researches have included another variable in the analysis of punching, effective mass (Neto, Magini, & Saba, 2007). Effective mass is defined in this thesis as the inertial contribution of the boxer to impact (Lenetsky, Nates, Brughelli, & Harris, 2015), and is calculated from the pre-impact velocity of the punch and the impulse produced during impact (Neto, Silva, Marzullo, Bolander, & Bir, 2012). This calculation reduces the boxer to a ballistic object that interacts with the target through the spring mass model, a common method of viewing punching throughout the literature (Neto et al., 2007). The less compliant the model the greater the effective mass (McGill et al., 2010). Inclusion of this variable in the literature is due to the potentially discriminating nature of the effective mass. Effective mass has been found to be a stronger measure of difference between trained and untrained punchers than peak force (Neto et al., 2012). However, the efficacy of effective mass over other impact kinetics is still unknown.

Rational and significance

Despite the fundamental nature of punching as a human movement and the long and storied history as a combat sport, there are still many areas lacking proper investigation. Early kinematic studies have served well to describe punching at a macro level, but have produced few findings into the essentials of optimizing punching performance. The theory of DPMA shows great promise as insight into one of the methods boxers use to improve impact kinetics, but lacks in situ investigation to confirm the theory. The reduction of punching to a purely ballistic action simplifies analysis, but may overlock much of the action. Research regarding the kinetics of the lower body have suggested that GRF may be a key determinant of punching performance, but like the above, lacks findings directly examining the lower body's contribution to impact kinetics. A greater understanding of lower body kinetics could provide insights into coaching and strength and conditioning interventions.

This thesis was designed to provide insight into the highlighted gaps and contribute to new scientific knowledge in the literature. This contribution to scientific knowledge was focused on the role of lower body kinetics and muscle activation patterns on the kinematics and impact kinetics of punches in boxers.

Thesis aims

The aims of this thesis were:

1. Determine if effective mass in the context of the spring mass model is an accurate representation of impact kinetics in punching.
2. Ascertain the importance of ground reaction forces in straight and hook punches in boxers.
3. Develop a phase model of straight and hook punches in boxers focused on ground reaction forces, muscle activation patterns, and kinematics.
4. Determine the role of muscle activation patterns and ground reaction forces in the production of effective mass, impulse, peak and mean force.

These aims combined to answer the central question of the thesis, "What determines effective punching in boxing?"

Thesis structure

This thesis was conducted under Auckland University of Technology's "Pathway 2", using a mixed method approach (Marshall & Rossman, 2014). As such, this thesis is comprised of three sections and seven chapters formatted for journal publication (Figure 1.) Most of the chapters have been submitted to international peer reviewed journals, which has allowed for feedback and improvement of the content.

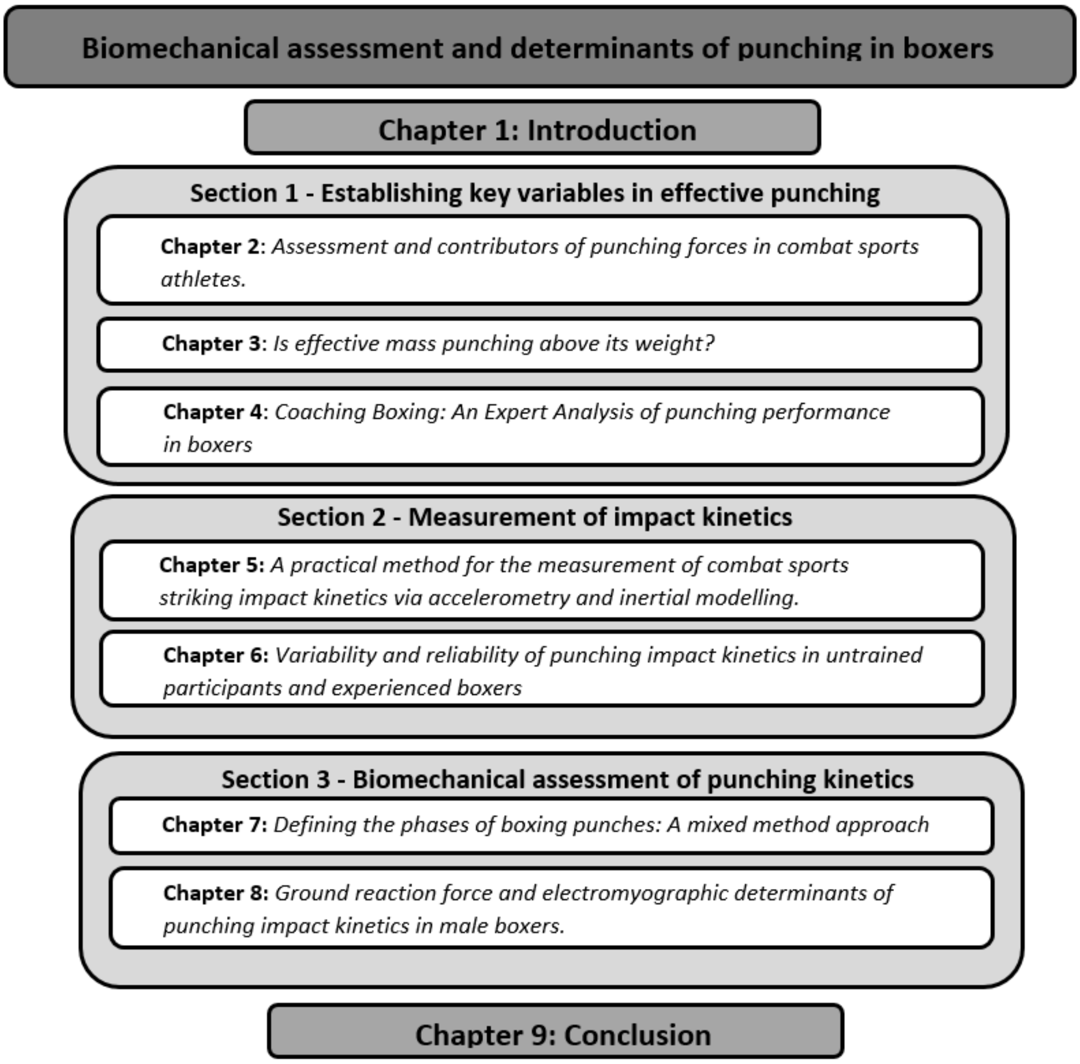


Figure 1. Thesis structure.

Chapter two of this thesis is a narrative review of current methods of assessment and the known contributors to impact kinetics in punching. The chapter also explored other sports with rotational components for insights into strength and conditioning practice. Recommendations were provided and based off the current literature. **Chapter three** is a narrative review of the impact kinetic variable effective mass. The chapter explored effective mass as it related to classical physics and the importance of the variable in combat sports. The methods used by combat sports athletes to improve effective mass is explored and the potential limitation of the spring mass model are addressed. **Chapter four** is a qualitative analysis of the views of boxing coaching on the components of effective punching. The findings were then compared to current biomechanical literature on punching. **Chapter five** presents a new method for measuring striking impact kinetics, the validation of that method, and an assessment of its reliability. **Chapter six** is a technical report on the inter- and intra-session reliability of the striking measurement method established in Chapter five on a cohort of boxers and untrained participants. **Chapter seven** is an experimental study using a mixed method approach to establish a phase model of straight and hook punches in boxers. Ground reaction forces (GRF) were used to establish the phases of each punch type and high-speed video and electromyography (EMG) data were used to expand the understanding of the defined phases. **Chapter eight** is the final experimental study of the thesis, aimed at using GRF and EMG data to establish the determinants of impact kinetics. This was performed through a hierarchical regression analysis to determine only those variables of utmost importance to impact kinetics. The concluding **Chapter nine** concludes the findings of the thesis, direction for future research, and provides practical interpretations.

Thesis format

The chapters that make up this thesis are formatted for publication (i.e. 'pathway 2'), and thus are written to be understood in separation from the thesis body, as such, there are some overlapping and repetitive themes throughout several sections of the chapters. In particular, the introductions of the majority of the chapters present similar information surrounding the current literature focused on punching in combat sports. Moreover, chapters six, seven, and eight (a. and b.) implement the same methods in part or whole and the same cohort of boxers. Chapter eight (a. and b.) is not formatted for individual publication, instead, the chapter combines two future publications into one in the aim to develop a wholistic understanding of the role GRF and EMG play in the development of impact kinetics for the purpose of the thesis. The final chapter, again not formatted for publication, features as a summary and practical interpretation of the publication chapters. Therefore, the final chapter does include some repetition in information and themes. Prefaces also have been added to each chapter to aid in narrative flow of the thesis.

Section 1:

Establishing key variables in effective punching

CHAPTER 2

ASSESSMENT AND CONTRIBUTORS OF PUNCHING IMPACT KINETICS IN COMBAT SPORTS: IMPLICATIONS FOR STRENGTH AND CONDITIONING

Reference

Lenetsky, S., Harris, N., & Brughelli, M. (2013). Assessment and contributors of punching forces in combat sports athletes: Implications for strength and conditioning. *Strength & Conditioning Journal*, *35*(2), 1-7.

Author contribution

SL: 90%, NH: 5%, MB: 5%

Preface

This chapter will review the current literature focused on methods used to measure impact kinetics and current theories into the key contributors to punching impact kinetics. This review serves as a backbone of the thesis, establishing how previous authors have measured impact kinetics, what is currently theorised to produce effective punching, and introduces theories that serve to address the thesis aims.

Abstract

Punching is a key component of striking-based combat sports. It has been established in boxing that the ability to apply force via punching to an opponent is paramount to victory. As such, it behoves strength and conditioning professionals to improve the punching impact kinetics of combat sports athletes in general. This review explores current research into the assessment of punching impact kinetics and contributors of punching impact kinetics, specifically ground reaction forces. Such information is vital for enhancing the scientific understanding of punching, and thus the development of optimum strength and conditioning strategies.

Introduction

The punch is a key component of boxing and various combat sports. It is used to inflict physical damage, develop tactical advantage and to score points against an opponent (Smith, 2006). Punching is a complex motion that involves movement of the arm, trunk, and legs (Turner, Baker, & Miller, 2011) but the lower body is considered a primary contributor to an effective punch (Filimonov et al., 1983). While speed and accuracy are needed for a punch to be effective (Piorkowski, 2011), several studies have shown that punching impact kinetics is paramount to a fighter's victory (Pierce et al., 2006; Smith, 2006). Research into punching has focused primarily on observing forces, with only one study of note focusing on potential training strategies for improving punching force (Turner et al., 2011). Utilizing research into the lower limb's involvement in punching and other similar movements, this review will examine the assessment of punching impact kinetics, and will further explore potential strength and conditioning strategies for improving punching impact kinetics.

Methods

The databases Google Scholar, Pro Quest and SportDiscus were explored for research relevant to punching with the truncated keywords "punch" and "strike", and combined with "sport", "combat sport", and "force". Additional relevant articles referenced within the manuscript gathered were included in the literature search as well. Of the forty-three articles found only those measuring punching impact kinetics or GRF (n=13) were included in this review. Most of these studies focused on the so-called "straight rear-hand" punch, also known as the "cross".

Measurement and analysis of punching impact kinetics

Punching impact kinetics can be measured and analysed to provide diagnostic information for programming, and prognostic information for talent identification and team selection. As one of the key indicators of performance, monitoring changes in punching impact kinetics can be used as a diagnostic tool for the design and efficacy of strength and condition interventions. Furthermore, the measurement and analysis of punching impact kinetics can be used as a prognostic tool for categorizing combat sport athletes according to their punching impact kinetics for a potential aid in team or program selection. Combat sports are in a unique position, lacking this important monitoring tool in common practice.

Throughout the literature a variety of devices have been used to attempt to monitor punching impact kinetics. While several unique designs have been used, such as pressure transducer submerged in water filled heavy bag (Fortin, Lamontagne, & Gadouas, 1995), and load cells in the neck of a dummy (Walilko et al., 2005), the most common design used to record punching forces is piezoelectric force transducers imbedded in a target (see Table 1)(Atha et al., 1985; Girodet, Vaslin, Dabonneville, & Lacouture, 2005; Smith et al., 2000). The preferential choice of using piezoelectric force transducers could be due to their accuracy, ease and proven reliability (CV = 1.8-3.6%) (Harris, 2010). The piezoelectric force transducers have been used to explore injury and health issues in boxers (Atha et al., 1985; Walilko et al., 2005) and to correctly identify boxer's experience levels through their punching impact kinetics (Smith et al., 2000).

Table 1. Dynamometry in punching impact kinetics literature.

Study	**Subjects**	**Force Measuring Equipment**	**Punches Tested**	**Punching Force (N)**
Atha et al. (1985)	Professional Heavy Weight Boxer (n=1)	Padded pendulum equipped with piezoelectric force transducer	Unidentified	4096(PF)
Fortin et al. (1995)	Unidentified	Water filled bag with pressure transducer	Unidentified	Not Included
Smith et al. (2000)	Elite (n=7), intermediate (n=8), and novice (n=8) boxers	Wall mounted force plate (four triaxial piezoelectric force transducers) with a boxing manikin cover	Elite rear hand mean force Elite front hand mean force Intermediate rear hand mean force Intermediate front hand mean force Novice rear hand mean force Novice front hand mean force	4800 ± 227 2874 ± 225 3722 ± 133 2283 ± 126 2381 ± 116 1604 ± 97
Girodet et al. (2005)	Karateka (n=1)	Makiwara equipped with two single axis force sensors	Straight Punch	1745(PF)
Walilko et al. (2005)	Olympic boxers weighing from 48kg to 109 kg (n=7)	Hybrid III dummy equipped with a six-axis load cell in the neck, a Tekscan pressure sensor in the dummy's face and Endevco accelerometers on the boxer's hands	Straight Punch	1990 to 4741(PF) 3427N ± 811(MF)
Pierce et al. (2006)	Professional boxers weighing 59.0kg to 98.9kg (n=12)	Bestshot™ force sensor imbedded in boxing gloves	N/A	866.6 to 1149.2 (MF) 5358 (PF)

PF= Peak Force MF=Mean Force

In a distinctive study design, Pierce et al. (2006) measured punching force from the fist of the fighter, rather than from the target of a punch. Using the Bestshot™ system Pierce et al. (Pierce et al., 2006) was able to have a force sensor placed inside of the gloves of boxers and have the resulting impacts transmitted via radio frequency telemetry to a computer during six professional boxing matches across multiple weight classes. This advancement in technology allowed for a flexibility of punch selection and, more importantly, the ability to record actual fight data. In addition, the system was found to be reliable and comparable with the mounted triaxial piezoelectric force transducers used by Smith et al. (Smith et al., 2000). A key finding by Pierce et al. (2006) was that peak and mean force outputs in the ring were substantially lower than those assessed in the laboratory. The authors note that hardest punch recorded by a heavy weight boxer registered 3554 N of peak force. This result was substantially lower than the 4800 N ± 227 found by Smith et al. (2000) and Atha et al.'s (1985) result of 4096 N. This discrepancy raises a potentially important issue. Laboratory and competition punching assessments may differ due to the dynamic nature of combat sports and as such should be further investigated to find if a direct relationship exists. Whether laboratory based or field based the current systems used to monitor punching impact kinetics report validity and reliability, and give the modern strength and conditioning practitioner an array of tools to quantify punching impact kinetics. Of additional interest is that Pierce et al. (2006) found that when a fight went to the judge's score cards the victor was, without fail, the athlete that had landed the greatest total force to their opponent. This result identifies the potential benefit of mean and peak punch force development by strength and conditioning practitioners.

Contributors to punching impact kinetics

The rear hand punch can effectively be broken into three primary contributors to punching impact kinetics: 1) the contribution from the arm musculature into the target, 2) the rotation of the trunk, and 3) the drive off the ground by the legs (Filimonov et al., 1983). Filimonov et al. (1983) analysed 120 boxers of varying ability and found that boxers with more experience had a greater contribution from their legs to the punch when compared to the other contributors (i.e. arms and trunk). Utilizing biomechanical observation and force dynamometry, Filimonov and colleagues found that in experienced boxers the legs contributed 38.6% of total punching force, compared to 32.2% for the intermediate and 16.5% for the novice boxers. Smith et al. (2000) assessed elite, intermediate, and novice boxers with a wall-mounted force plate and found that experience linked to greater punching force. Elite boxers produced 4800 ±227 N in peak force during the rear hand punching, while intermediate and novice boxers produced 3722 ±133 N and 2381 ± 116 N, respectively. The findings of the previous two studies suggest that the greater the contribution from the legs to the punch, the greater the force. In support of such a contention, Filimonov et al. (1983) grouped the subjects by their stylistic preference as “knock-out artists”, “players” and “speedsters”. The study found that “knock-out artists” had leg drive contribution that was higher (38.6%) than the subjects grouped as “players” (32.8%) or “speedsters” (32.5%) whom relied more on a contribution from trunk rotation.

In contrast with the results of Filimonov et al. (1983), Mack et al. (2010) found a greater relationship of punching forces in 42 amateur boxers to pre-impact hand velocity (0.39 and 0.38 R^2) rather than to the forces generated by the athletes' legs (0.10 and 0.10 R^2). It is worth noting that the authors assessed the contribution from the legs via the “unique” FAB system (FAB goes undefined), which estimated force from the dominant leg during the punches. A potentially more valid and reliable measure of leg GRF would be a measurement from a force plate, which could be combined with a motion capture system to further explore Mack et al.'s (2010) conclusions. Comparison of pre-impact hand velocity and leg drive may not be appropriate; leg drive most likely affects and develops pre-impact hand velocity. In many ways what Mack et al. (2010) explored in their study would be the same as comparing a baseball's - velocity pre-impact to a pitcher's lower body contribution during the wind up. The lower body has already imparted its energy into the ball, so any comparison of the pre-impact velocity of the ball is affected by that input (Laudner, 2010). Likewise, the legs contribute to hand velocity during punching movements (Turner et al., 2011). An additional and potentially more relevant association to examine is leg drive with the pre-impact hand velocity rather than punch forces on impact with pre-impact hand velocities.

In summary, there is a conflict in current research regarding the importance of leg drive to punching power which requires further exploration.

Investigating other sports which follow roughly similar movement patterns, the importance of the lower body's contribution is seen throughout the literature. An analysis by Terzis et al. (2003), found that elite shot putters contributed roughly half of their throwing performance from the lower body. Exploring overhead throwing in children Stodden et al. (2006) found an improvement in ball speed from 8.41 ± 5.45 to 14.20 ± 4.5 m/s^{-1} with the inclusion of an ipsilateral step and a further improvement to 28.10 ± 1.6 m/s^{-1} with a more punching specific (Turner et al., 2011), contralateral step. A study by Bouhlel et al. (2007) found that in national level javelin throwers, performance correlated strongly with maximal anaerobic power per kilogram ($R=0.76$, $P<0.01$) and maximal velocity ($R=0.83$, $P<0.001$) produced by the legs during a force-velocity test. These findings indirectly support the conclusions by Filimonov et al. (1983) about the importance of leg drive to develop punching impact kinetics.

Potential strength and conditioning strategies for improvement of punching impact kinetics

No studies were found that explored in depth the impact of strength and conditioning practice on punching impact kinetics. Hence, this review will examine boxing studies that have superficially addressed the issues and look at other sports that have explored the effects of strength and conditioning practices in greater depth. To achieve the goal of increasing leg drive during a punch, Filimonov et al. (1983) and Turner et al. (2011) both suggested the use of axial loaded movements such as squats, weightlifting variations (snatch, clean, jerk, etc.) and vertical jumps. While the argument for axial loading appears sound, these movements only occur bilaterally and in the vertical direction. Leg drive during punching requires GRF to be developed not only in the vertical but also in horizontal directions, with various staggered stances. Depending on the primary direction of the GRF during punching it may be more appropriate to emphasise longitudinal movements, such as sled pulling, jumps and throws seen in Table 2.

An argument in favour of vertical GRF being the primary factor in the punch can be extrapolated from a study by Akutagawa and Kojima (2005) exploring back hand shots of 14 male colligate tennis players. The authors found substantially greater vertical GRF than horizontal GRF in subjects as they hit tennis balls. This may be applicable to understanding GRF during punching as part of the tennis player's back hand technique utilized rotation of the pelvis in a similar manner to that found in many forms of punching.

In contrast, support for horizontal GRF as the primary factor in punching impact kinetics is found in Cesari and Bertucco (2008), who observed large changes in the centre of pressure (COP) anteriorly/posteriorly as karatekas (karate practitioners) punched a target. The study also compared experienced to less experienced karatekas and found that with experience there was a greater COP movement anteriorly and less posteriorly. While, Cesari and Bertucco (2008) focused their results on the karateka's ability to maintain dynamic stability, this study still helps to illustrate the directionality of the force during a punch. Similarly, Gulledge and Dapena (2008) found high levels of horizontal force in rear hand punches recorded on a force plate but unfortunately did not examine vertical forces. A strength of both studies was the inclusion of a force plate to assess the participants. If future research corroborates these findings a strength and conditioning practitioner would be well served to focus on longitudinally loaded movements to complement the axial loaded movements suggested by Filimonov et al. (1983) and Turner et al. (2011).

A third theory in regard to the specificity of GRF in the punch may be proposed. There may be no singular GRF direction that is optimum for improved force production. As a movement that involves rotation of the pelvis, trunk, and shoulder (Turner et al., 2011) both vertical and horizontal force may contribute near equally to the punch in a rotary movement. Until further research exploring the directional application of leg drive, current strength and conditioning practitioners are reliant on an incomplete picture of punching and the components that affect it.

Practical applications

Utilizing the literature reviewed in this article, basic strength and conditioning suggestions can be provided for the development of punching impact kinetics in combat sports athletes. First and foremost, it is recommended that lower limb strength and power are considered for improving punching impact kinetics, seen in Table 3. While strength and power are also important for both the upper body and the core in a more general sense, this section will focus on specifics for improving punching impact kinetics as currently understood from the literature. That is, the development of lower body strength and power, core stability, and upper limb velocity. In regard to training the lower limbs for punching, there is currently a paucity of research exploring the specificity of GRF direction. It is the view of the author to focus equally on axial loaded movements (e.g. squats) and longitudinally load movements (e.g. sled pulls).

Punching is an extremely dynamic motion that occurs over a very short time period (Atha et al., 1985). In order to properly prepare an athlete for a combat sport, it is important to develop force and velocities capabilities with the ultimate goal of producing the greatest total power output (Siff, 2004). While there are many methodologies to produce such adaptations in athletes via periodization, this review will use the framework of linear periodization (Bompa, 2005) to communicate training suggestions. The utilization of linear periodization in this review is for communication rather than recommendation of training progressions.

Following basic linear periodization (Bompa, 2005), development of a maximal strength base is necessary during the general preparation phase. For the development of punching impact kinetics, it would be appropriate to use axial and longitudinal exercises e.g. the squat for the development of vertical GRF and heavy sled pulls to develop horizontal GRF. Once a maximal strength base has been developed, it is then appropriate to focus on a conversion to power during the specific preparation phase. Weightlifting movements (clean, snatch jerk, etc.) could be used to develop axial power, and medicine ball or shot throws to develop longitudinal power. It is important to ensure when training for strength and power that appropriate rep ranges, loads and rest periods are used. Possibly most important for combat sport athletes with the goal of increasing maximal strength and power for GRF development is the need to rest 2-5 minutes between sets (Baechle, 2008).

Table 2. Training recommendations.

Strength	Power	Sport Specific
Axial- Squat variation Deadlift variation Lunge variation Single leg squat variation *Longitudinal-* Hip thrusts and bridges Sled pulls (high load) Pull throughs	*Axial-* Weightlifting variations Rubber band or chain addition to the strength movements Push press variation Vertical jumps *Longitudinal-* Medicine ball/shot throws horizontally Sled pulls (lower load) Horizontal jumps Greek long jumps	Punches (single or in combination) Complex training (near-maximal strength exercises followed by punches)

Rest periods are a focus, as there are numerous pieces of literature which recommend circuit training for the conditioning of combat sport athletes (Amtmann, 2003; Schick, 2012). This focus may lead to an inappropriate emphasis on low rest resistance training despite the authors' intent to inform conditioning practise not maximal strength training practice. A lower rest period between exercises will result in greater fatigue and consequently lower load use. When the goal of a strength and conditioning professional is to improve maximal GRF, longer rests are needed to allow for bioenergetic restoration and thus true maximal efforts (Baechle, 2008), resulting in a neuromuscular stimulus rather than a metabolic. These recommendations are seen in full in Table 3. When training for the pre-competition phase, the focus of a strength and conditioning professional should be on continued improvement of power but in a sport specific context. For combat sport athletes this could be accomplished through single or combination punches thrown on a bag or pad with rest periods utilized for the development of power (Jamieson, 2010). This recommendation again stands in contrast to commonly given advice for combat sports athletes regarding bag or pad work, as it is primarily used as a conditioning tool and not a tool for the improvement of strength and power. Additionally, the punch training for strength and power could be used along with near-maximal strength movements to take advantage of post activation potentiation, and further improve punching impact kinetics.

Table 3. Strength and power guidelines.

Training Goal	Goal Repetitions	Sets	Rest Period Lengths
Strength	≤6	2-6	2-5 Minutes
Power Single-effort Multiple-effort	 1-2 3-5	 3-5 3-5	 2-5 Minutes 2-5 Minutes

Regarding core training for punching, it is the recommendation of the authors to focus on lumbar stability training in relation to the rotational forces in the punch. An emphasis on lumbar rotational stability, rather than movement is indicated to allow for a transmission of GRF through the lower body and into the upper body before making contact with an opponent (Harris-Hayes, 2009; McGill, & Cholewicki, 2001). A stretch shorten cycle (SSC) has been observed during punching (Turner et al., 2011) and other similar movements (Urbin, 2012). By stiffening the lumbar spine through stabilisation movements like those suggested, an improvement in trunk SSC could occur similarly to that seen in joint stiffness after resistance and plyometric training (McMahon, 2012). Additionally, if mobility is over-emphasized rather than stability the potential of injury is also increased due to movement in the lumbar (McGill, 2007; Norris, 1995), along with a potential reduction in punching impact kinetics. Differing from the lower body progression of exercises it is recommended that core exercise progresses in difficulty to stabilize rather than a maximal strength to power paradigm. Moving from floor based movements like the prone quadruped to kneeling exercises like the split stance cable row and finally standing exercises like the pallof press. As the purpose of these exercises is to stabilise throughout the entirety of a bout, training stimulus should be focused on developing endurance to improve the fatigue resistance of musculature and enable it to resist the potentially high forces produces by the lower body.

Finally, and indicated by the literature as of least importance for improving punching impact kinetics is upper body training. Current recommendations from Turner et al. (2011) suggest a focus on ballistic training to increase the velocity of strikes. As little literature has explored punching in relation to the upper body and there is little relevant data that can be looked to from other sports, baseball pitching is too dissimilar and track and field sports utilize implements that have too great of mass, the recommendations from Turner et al. (2011), included in Table 4, would be the most appropriate to implement with the current knowledge base.

Table 4. Upper body training recommendations from Turner et al (2011).

Strength	Bench press Overhand chin up Bent over row
Power	Bench press throw (Load according to power curve)
Options for complex training	Medicine ball throws Clapping push ups

These suggestions, while basic, do serve to produce a frame work onto which a strength and conditioning professional can further explore the development of punching impact kinetics.

Conclusion

Research into punching has illuminated various potential key performance contributors, but has yet to fully examine their impact on punching performance. Similarly, GRF studies have explored multiple sports, but have only assessed punching superficially. Advancements in the understanding of one or both of these areas could greatly improve strength and conditioning practices for punching performance. Current technology is capable of assessing punching impact kinetics and allows for research into punch contributors and GRF to occur easily. As such, the stage is set for the first many studies to truly develop an understanding of punching and how to best train athletes to improve their punching.

CHAPTER 3

IS EFFECTIVE MASS IN COMBAT SPORTS PUNCHING ABOVE ITS WEIGHT?

Reference

Lenetsky, S., Nates, R. J., Brughelli, M., & Harris, N. K. (2015). Is effective mass in combat sports punching above its weight? *Human movement science*, *40*, 89-97.

Author contribution

SL: 85%, RJN: 5%, NH: 5%, MB: 5%

Preface

With Chapter two's establishment of the methods to measure and the contributors to punching impact kinetics, this chapter reviews what has been suggested in the literature to be potentially the most important impact kinetic in punching, effective mass. The chapter established effective mass as an important variable, but only one of many, and proposes a competing theory to the spring mass model explanation of effective mass. Chapter three adds to Chapter two's foundation of the thesis by outlining further gaps in the literature that the thesis aims address in the later chapters.

Abstract

The segmental and muscular complexity of the human body can result in challenges when examining the kinetics of impacts. To better understand this complexity, combat sports literature has selected effective mass as a measure of an athlete's inertial contribution to the momentum transfer during the impact of strikes. This measure helps to clarify the analysis of striking kinetics in combat sports. This paper will review: 1) effective mass as a concept and its usage as a measure of impact intensity in combat sports, 2) the neuromuscular pattern known as "double peak muscle activation" which has been theorised to help

enhance initial hand velocity upon impact and joint stiffening during impact, 3) the methods and equations used to calculate effective mass, and 4) practitioner recommendations based on the literature. We will argue in this thesis chapter that the act of punching presents unique challenges to the current understanding of effective mass due to additional force application during impact. This review will improve the understanding of effective mass and its roles in effective striking serving to underpin future research into performance enhancement in striking based combat sports.

Introduction

In the seminal work *Tao of Jeet Kune Do* (Lee, 1975) author and martial artist Bruce Lee brings the reader's attention to the importance of relaxing their body as they strike, tensing at the last possible moment before impact. It is suggested by Lee that this will produce a strike of great force. Similarly, the world champion boxer Jack Dempsey (1950) writes in his 1950 guide to boxing *Championship Boxing* that punches should be thrown as relaxed as possible only to become "frozen, steel hard" at impact. These great athletes are referring to methods that they have anecdotally experienced as being effective in transferring momentum in their strikes. Intuitively the advice makes sense, but lacks what is commonly seen in combat sports, a scientific rationale (Lenetsky & Harris, 2012). In the context of our current scientific understanding this would be interpreted as maximising the effective mass of the strike (Derrick, Dereu, & Mclean, 2002). If an athlete is able to increase the effective mass of their strike (i.e. inertial contribution), they will transfer more momentum at impact. If an athlete can relax their arm throughout a strike, and then stiffen their arm at the last possible moment, theoretically that strike would impact with greater force than one thrown with constant activation. The stiffening of the arm gives a better connection of the hand to the rest of the body, utilizing some of the momentum of the body. This paper will explore the theory of effective mass and its relation to momentum transfer in a strike. The current literature will also be examined regarding both the monitoring of effective mass and muscular activation in combat sports and the methods by which combat sport athletes modify their potential to enhance effective mass. Finally, a series of evidence based recommendations for the modern combat sport athlete to utilize in the practical environment are proposed.

Effective mass

Effective mass as a concept

As shown in the previous paragraphs, this term "effective mass" has become a common parameter in the sports science community. To understand effective mass, we first must look at its use in ballistic spring mass modelling. The spring mass model is used in sports science to simplify the complexity of the human body (Blickham, 1989). Traditionally, effective mass used in the spring mass model has been applied to ballistic impacts, such as, kicking a ball, lands on trampolines, and contact during running (Derrick et al., 2002; Khorashad, 2013; Southard, 2014). The spring mass model breaks the body into a simple construct of a massless springs connected to blocks of mass (Blickham, 1989; Derrick, Caldwell, & Hamill, 2000). This simplified model allows for a conceptual understanding of impacts relating to the human body.

If an athlete was a solid uniformly shaped block of mass, determining the impact force and effective mass upon impact would be a simple calculation of the mass of the whole system and the acceleration it was experiencing (Derrick, 2004). In this example, the effective mass would simply equal the mass of the system. Instead, athletes are made of multiple moving segments, containing both rigid structures (bone) and soft structures (muscle, tendon and ligaments), which upon impact can deform, reducing impact forces (Gruber, Ruder, Denoth, & Schneider, 1998). The deformation prone mass in humans has been referred to as “wobbling mass” and is unable to transmit impact forces as effectively as rigid mass (Gruber et al., 1998). During a collision the greater the rigidity of the impacting mass, the less elastic the collision. The less elastic a collision, the greater the momentum imparted into the target or opponent (Pain & Challis, 2002).

To properly quantify impacts of the human “wobbling mass”, effective mass is used. Effective mass reflects the spring stiffness in the spring mass model and the role that the various blocks of mass play in that impact by equating the human shaped “wobbling mass” as a single uniformly shaped mass that has a similar elasticity to every involved segment. For example, Derrick et al. (2002) examined the impacts of participants during an exhaustive run. Rather than only exploring the impacts as a result of the mass of the body as a whole, Derrick et al.’s (2002) use of effective mass accounts for the mass of the foot and some of the mass of the leg, torso, and even upper extremities. Additionally, the use of effective mass accounts for the stiffness in the joints of the entire kinetic chain involved. In a later paper Derrick (2004) provides an equation (Equation 1) to calculate effective mass based on the impulse-momentum relationship seen below:

Equation 1

$$m_e = \frac{1}{\Delta v}\int_{t_1}^{t_2} F dt$$

where, m_e is the effective mass of the body, Δv is the change in velocity and $\int_{t_2}^{t_1} F dt$ is the linear impulse from the impact. What this equation demonstrates is that Derrick et al.’s (2002) measure of effective mass in runners could also be viewed as the runner’s inertial contribution to the transfer of momentum between the participant and the landing surface at the point of impact.

Effective mass in the context of combat sports

The equations of dynamics used to define effective mass in combat sports (Neto et al., 2007; Neto et al., 2012; Walilko et al., 2005) are based on the simple effective mass model that replaces the striking agent (arm or leg) with a rigid ballistic mass (Figure 2). It is assumed that this ballistic mass flies at the target and strikes it with a measured incoming velocity, transfers all its momentum to the target and causes the target to fly off at a measured exit velocity. The derived equations permit the calculation of an "effective mass" of this ballistic item, and this value is used as an indicator of the effectiveness of the strike. Although theoretically and technically accurate, it is felt that this ballistic model removes some of the understanding of the momentum transfer in the impact.

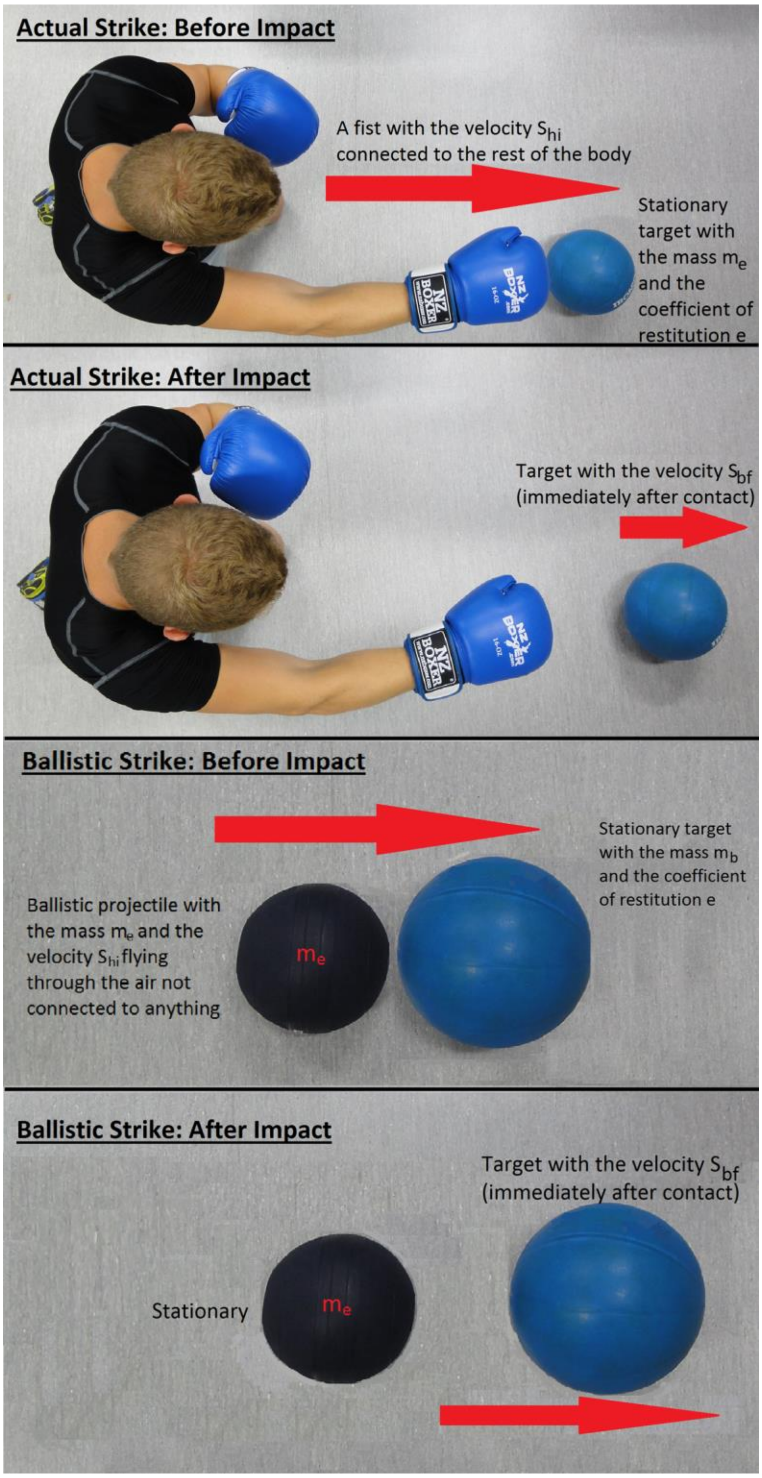


Figure 2. Differences between an actual strike and the ballistic modelling of effective mass.

Combat sport studies have found that an increase in muscle contraction and co-contraction around a given joint can cause a reduction in the deformation seen during impact, which allows for a greater total effective mass involved in the impact (McGill et al., 2010; VencesBrito, Ferreira, Cortes, Fernandes, & Pezarat-

Correia, 2011). Additionally, the more segments an athlete can involve in a movement the greater the potential to enhance effective mass. Walker (1975) provided an example of this in the context of combat sports by hypothesising that if a karateka (Karate practitioner) were to step forward while punching they would increase their effective mass in the strike, increasing the impact forces beyond that which would be seen if only the arm was involved in the strike. The additional momentum added by the forward step was termed by Walker (1975) as "follow through".

At the start of impact, two aspects of mechanics need to be satisfied in order to transfer momentum. Firstly, all the joints supporting the impact need to be stiffened to prevent collapse of the joint. Secondly, we theorise that to maximise the effectiveness of a punch an additional force needs to be added during the time of impact. It is our position that this force needs to be timed carefully to coincide with the deceleration of the impact, as it is only during this time that force may be effectively applied. Force applied very late, or after impact could be theorized to push at the target rather than deform it.

This momentum transfer is created in theory by joint stiffening and additional force contribution by the striker during the impact. The traditional ballistic model of effective mass derived from the spring-mass model is most appropriate for examining inertial contribution from joint stiffening without additional force contribution. Where this model is limited as a concept is when additional forces are applied during an impact, and thus we believe it does not fully explain the process of human striking. The findings by Neto et al. (2012) echo this statement as increased peak punching forces were found in non-dominant hands while stepping forward, while effective mass did not change. Neto et al. (2012) attribute this discrepancy to the concept of "follow through" as proposed by Walker (1975). This discrepancy could also be explained by the limitations of effective mass. As stated above, peak force and effective mass should be viewed as very separate but equally important parts of a holistic understanding of striking. It is possible that the athlete's non-dominant strikes were able to produce high peak force early due to a number of reasons and then lacked effective mass due to poor joint stiffening and contribution of force throughout the strike. Regardless of the cause of this discrepancy, it underscores the importance of the use of different measures of punch kinetics to truly understand what is occurring. The discrepancy also indicates a need for further research into an understanding of which measures are indicative of effective punching.

A further issue concerning effective mass is that some researchers seem to describe the ability of a practitioner to vary effective mass during the process of a strike (i.e. from the initial acceleration through to impact) (Blum, 1977). This is clearly using the term outside of its definition, which is only valid as an equivalent ballistic mass during impact. In order to achieve a certain impact velocity every strike involves the acceleration of the actual mass to the impact velocity. This actual mass cannot be changed in any way, however different muscle groups and motions could be used to greater or lesser effect in achieving the necessary acceleration as stated above. What does vary throughout the punch is the potential to enhance effective mass. If impact were to occur in an early phase of the punch, perhaps due to movement of the target, when the musculature is relaxed and ground reaction forces are not applied appropriately the effective mass would be lower than if impact occurred at the athlete's desired target position, where effective mass would be maximized. This may be seen as a semantic argument but aids in clarifying the definition of effective mass and ensures that the concept does not lead to a paradigm that it is thought that actual mass can change or that effective mass can be calculated anywhere except during impact (Derrick, 2004).

Effective mass during strikes

Currently there is a paucity of research examining effective mass in combat sport athletes (McGill et al., 2010; Neto et al., 2007; Neto et al., 2012; Walilko et al., 2005). There is also no agreed upon equation for the calculation of effective mass found in the literature. As such, we have included all of the equations identified for calculating effective mass in combat sports in this section and presented the papers in chronological order to display the changes in this field of study. We have used the same symbol for effective mass in all equations to provide clarity and consistency. Of note, the extensive research by Walilko et al. (2005) focused on head injuries in Olympic boxers found that the key variable to punching impact kinetics in the boxers tested was the calculated effective mass of the punches. The effective mass of the punches was calculated using the Equation 2

Equation 2

$$m_e V_p = (m_h + m) V_h$$

where the velocity of the punch is V_p, the velocity of the target after impact (the head of a Hybrid III dummy in this study) is V_h, m is the mass of the target, and m_e is the effective mass of the puncher's hand. This equation relies on the concept of the conservation of linear momentum to find effective mass. The authors found an average effective mass of the punches thrown was 2.86 ±2.03 kgs.

The authors identified no significant differences in the punching velocities of all the tested boxers, across all weight classes. However, there were significant differences in the punching impact kinetics measured. These differences correlated (r= .66) to the effective mass of the punch, which can be inferred to be caused by joint stiffening (McGill et al., 2010; Neto et al., 2007) and/or additional forces produced during impact by the boxers. Interestingly, Walilko et al. (2005) also found that there was a strong correlation found between punching velocity and effective mass (r=0.76). While the authors provided no insight into the underlying factors in this relationship, it may relate to the muscle activation, relaxation, and re-activation pattern seen in other studies and proposed to be the key neuromuscular component to varying potential effective mass (McGill et al., 2010).

Investigating only hand speed and effective mass in kung fu practitioners and non-practitioners, Neto et al. (2007) found that both attributes were greater in trained participants, tested via an inventive study design utilizing a basketball as the striking target. The basketball was first dropped in order to determine its coefficient of restitution, which was then used in the formula for effective mass (Equation 3)

Equation 3

$$m_e = \frac{m_b \, s_{bf}}{s_{hi}(1 + e) - s_{bf}}$$

where m_e is the effective mass of the strike, m_b is the mass of the ball, s_{hi} is the hand speed of the athlete before impact, s_{bf} is the ball speed after impact, and e is the coefficient of restitution of the ball. The coefficient of restitution is a value which represents the velocity of objects after an impact and can be used to determine the elasticity or inelasticity of objects during impact. This equation developed by Neto et al. (2007) uses the conservation of linear momentum, much like Walilko et al. (2005), and the coefficient of restitution of the target to establish a more complete calculation of the striker's effective mass.

Neto et al. (2007) reported that the kung fu practitioner's strikes had an effective mass of 2.62±0.33 kgs while the non-practitioners had a significantly lower (p = 0.004) effective mass of 1.33±0.19 kgs. The differences seen in Neto et al. (2007) appear to indicate an adaptation from kung fu training that allows for athletes to develop greater effective mass. Thus, it is highly plausible that kung fu training enables practitioners to add in greater force during impact, which raises the effective mass.

In a more recent study by Neto and colleagues (Neto et al., 2012), incongruities were found in comparison with previous papers measuring effective mass (Neto et al., 2007; Walilko et al., 2005) Effective mass was measured at 1.42±0.302 kgs in the dominant hands of male Kung Fu practitioners and 0.92±0.32 kgs in the dominant hands of female Kung Fu practitioners. These finding are far lower than the 2.62±2.03 kgs found in Kung Fu practitioners by Neto et al. (2007) and 2.9±2.0 kgs in boxers by Walilko et al. (2005). It is noteworthy that the most current study by Neto et al. (2012) used a far different method to measure effective mass than the previous studies (Neto et al., 2007; Walilko et al., 2005). Utilizing high speed cameras and a pendulum mounted load cell, Neto et al. (2012) were able to establish a more direct kinetic measure of effective mass. The resulting force data from the load cell (F) and instantaneous hand speed from the high-speed video (S) were analysed as an integral between the instant of impact (t1) and the instant the hand was seen to stop (t2) as viewed through the high-speed cameras to establish effective mass (M_e).

Equation 4

$$M_e = \frac{\int_{t2}^{t1} F\,dt}{S}$$

The authors note that Equation 4 is in fact a measure of the strikes impulse divided by the hand speed before impact (Neto et al., 2012). It is important to note that the integral is used in this more current paper, rather than the final momentum (of the ball) as in the previous papers (Neto et al., 2007). This equation accounts for the variable force that occurs during the fist-target contact period, and separates the terms effective mass and peak force which are two different aspects of the impact. The peak force being measured by a transducer occurs at only one point during the impact, whereas effective mass integrates all of the points on the force curve to give a ballistic equivalent to the total momentum transfer process. Although not mentioned in Neto et al. (2012), it can be deduced that these are two different measures of the impact process and thus would depend on different aspects of the striking technique. For instance, a technique could produce a very high peak force for a small period of time and result in a relatively lower effective mass. Conversely, a lower peak force sustained for a long-time duration could result in a relatively greater effective mass. These two types of strikes would likely have different effects on targets that were more or less ridged, or had greater or lesser inertia.

Neto et al. (2012) further found that effective mass had no linear association with hand speed (R^2 =.058). This result stands counter to the findings of Walilko et al. (2005), although the authors did not comment on this. However, Neto et al. (2012) did find that the product of effective mass during the impact and hand speed prior to impact were strongly correlated with peak punching force (R^2 =.853). These contrasting, unexplained findings indicate a need for further research into effective mass and punching kinetics.

The findings of Neto et al. (2007) suggest that the effective mass of the strikes were actually greater than the mass of the utilized hand. This difference could have been caused by stiffening of the arm (VencesBrito et al., 2011) resulting in a greater transfer of momentum (Walker, 1975), and/or additional force applied during the. Additionally, this increased effective mass was found by Neto et al.

(2007) to have no relation to the body mass of the athletes, which is understandable as a technique modification rather than an effect of body mass. The studies by Walilko et al. (2005) and Neto et al. (2007) both serve to establish an understanding of effective mass in striking as an important and trainable attribute of combat sport athletes.

"Double peak muscle activation" in review

Stuart McGill and colleagues (McGill et al., 2010) identified the key neuromuscular phenomenon thought to cause changes in effective mass. Described as "double peak muscle activation" due to the activation, relaxation, and re-activation of the involved muscle groups, this striking technique was found to occur in elite mixed martial artists and their coaching staff. The study explored a variety of arm and leg based strikes both in standing and grappling contexts, analysing the muscle activation via electromyography (EMG) electrodes located on the abdomen, thorax, hip flexors and extensors. The double peak pattern activation followed a similar pattern for the majority of strikes tested, starting with an EMG peak (indicating muscle activation) as the movement was initiated, then a drop in EMG throughout the movement, and a final EMG peak, moments before impact. A general representation of this can be seen in Figure 3.

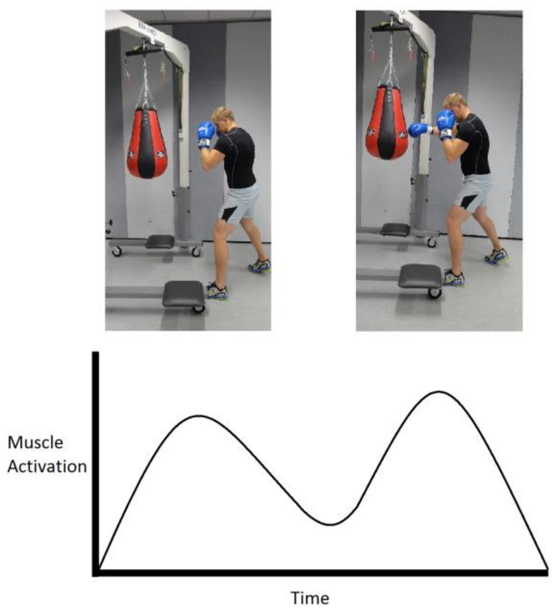


Figure 3. A general representation of the double peak activation pattern throughout a rear hand punch.

The physicist Haywood Blum intuitively understood double peak muscle activation, claiming that it is a result of “focus” (Blum, 1977). Focus could allow for a reduction in muscle force production in the strike which will result in greater hand velocities upon impact. Blum’s (1977) supposition appears to demonstrate the physiological phenomenon of the force-velocity relationship. The force-velocity relationship is characterised by a reduction of force production in a quasi-linear association with velocity during multi-joint movements (Bobbert, 2012). In combat sports velocity is a needed attribute to appropriately interact with an opponent (Lee, 1975), but appropriate levels of impact force are also needed to be effective in that interaction. An athlete must find a way to maximize both attributes. Several authors have explored double peak muscle activation as a mean to circumvent the limitations inherent in the force-velocity relationship and result in a strike with enhanced velocity and force (McGill et al., 2010; Neto et al., 2007; VencesBrito et al., 2011).

VencesBrito et al. (2011) found similar EMG results to that of McGill et al. (2010) with double peak muscle activation occurring in the arm musculature of karatekas and untrained participants. Of note, VencesBrito et al. (2011) found the double peak activation in the antagonist muscles of the punching arm. With the first EMG peak assigned by the authors as a stabilizing contraction and a second EMG peak just prior to impact. VencesBrito et al. (2011) establish that non-trained participants tended to have a double peak activation similar to the trained participants, but that in the non-trained participants the second peak occurred much earlier and lasted longer. Furthermore, the study found that the EMG results showed a proximal to distal activation pattern in the punching process. This raises an interesting question, as it has been well established that various complicated movements follow such a proximal to distal muscle activation pattern (Putnam, 1993). It is unknown if the second EMG pulse that increases joint stiffening is similarly proximal to distal across all involved muscle groups or simultaneous. A simultaneous activation may serve to better increase effective mass, “locking” the striking limb into a single unit (Blum, 1977), reducing deformation upon impact (McGill et al., 2010; VencesBrito et al., 2011), and linking of the striking limb to the mass of the body producing a great transfer of momentum (Walker, 1975). Simultaneous activation was seen in the trunk musculature analysed by McGill et al. (2010), but it is still unknown if this occurs in the limb musculature as well. Further exploration is needed in this area, perhaps following the protocols of McGill et al. (2010) and VencesBrito et al. (2011) simultaneously.

From the literature, it is seen that in most cases double peak activation exists, but that the timing differs. VencesBrito et al. (2011) noted that even the novices showed a second peak activation, but this occurred much earlier than the experienced practitioners. From the forgoing discussion, this can be understood as follows: Even a very inexperienced practitioner will learn intuitively to stiffen the joints before impact, after only a few punches so as to protect the impact zone and limbs. In fact, it is likely that they will always tense these muscles early in anticipation of the impact. This early second activation will tend to slow the impact velocity, and thereby reduce the effective mass. Whereas a skilled practitioner will tense at the moment of impact and continue to push through the impact in order to both prevent joint collapse and produce significant force during impact. It is believed that the level of skill in achieving this is the difference between novice and expert.

Practitioner interventions

Currently there has been no research into technique or strength and conditioning interventions which may improve an athlete's ability to enhance effective mass. What has been established in the literature are a series of suggestions regarding how an athlete could theoretically enhance effective mass (Turner et al., 2011). First and foremost, the greatest effector on striking effective mass is experience. That is, the more an athlete punches targets, the better he/she will be at enhancing their effective mass. While it is unknown if coaching cues similar to that provided be Lee (1975) and Dempsey (1950) are paramount to increasing effective mass or if through the inherent learning constraints of punching a target the athlete develops these attributes (Davids, Button, & Bennett, 2008). What has been found in multiple studies is that experience is a major contributor to greater effective mass. Utilizing both concepts of coaching cues and learning constraints to train a combat sport athlete could help to improve effective mass. In addition, the use of a “kiai” or “energy shout” is indicated by the literature to be a potential mean to increase effective mass (Turner et al., 2011). By adding a “kiai” to the final pre-impact portion of a strike, it would be expected to see greater improvements in effective mass.

Additionally, repeated training bouts of high velocity movements have been shown to increase speed of motor unit recruitment (Agaard, 2003). This would be a useful adaptation as it allows for a last moment contraction of the musculature. To best utilize this information, a programme including high load movements, medium load/high power movements, and low or no load/high velocity movements would complement an athlete’s skills learned through striking experience, and allow for greater effective mass by increasing the time spent relaxed and then contracting with great intensity moments before impact.

Conclusion

Current literature indicates that effective mass is one of the key components to an athlete’s striking performance. It is also apparent that improved effective mass is a learned skill that could be improved through appropriate practitioner interventions. While not a foreign concept to combat sports, a true understanding of the mechanics of such a process will serve to improve the training of current and future combat sport athletes. Further exploration is needed to establish a complete understanding of key punching kinetic variables and effective mass’s place among those variables. Furthermore, it is apparent that more research is needed into the exact mechanics of muscle activation/deactivation relating to effective mass and beyond that, studies of both technique-based and strength and conditioning-based interventions are needed to develop protocols for this important attribute.

CHAPTER 4

COACHING BOXING: AN EXPERT ANALYSIS OF PUNCHING PERFORMANCE IN BOXERS

Reference

Lenetsky, S., & Lindsay, R. (2017). Coaching Boxing: An Expert Analysis of punching performance in boxers. *Qualitative Research in Sport, Exercise and Health*, In prep.

Author contribution

SL: 90%, RL: 10%

Preface

To further compliment the conclusions of Chapters two and three, Chapter four is a qualitative study into the views of boxing coaches on effective punching. Rarely in the literature are the qualitative concepts and theories of coaches utilized directly in concert with quantitative analysis. By combining such information, it ensures the further chapters in this thesis are relevant to researcher and practitioner alike, and more importantly stands as a check against confirmation bias potentially developed in the literature review process. Additionally, this thesis chapter confirms that the coaches' knowledge is based on relevant scientific concepts and not misinformed socially generated coaching practices. This chapter combines qualitative and quantitative methods in the thesis, strengthening the rationale for the thesis aims, and the methods used to explore them.

Abstract

Of the research investigating punching biomechanics, an in-depth investigation into expert coaching knowledge remains unaddressed. Any such examination would serve as a pathway to developing a holistic understanding of punching. The aim of this study was to identify characteristics that expert boxing coaches associate with effective punching. Five professional and amateur boxing coaches

participated in this study, with data being gathered through in-depth, semi-structured interviews. A constant comparative approach was used to analyse the data. Four principal components emerged from the interview data. These included: 1) whole body movement, 2) footwork, 3) hip and shoulder rotation, and 4) hand and arm position. The establishment of these four components of effective punching were supported by findings in existing boxing literature with respect to the biomechanics of punching. This study highlights the current gap in knowledge regarding effective punching technique, an area that requires further investigation before conclusive structures of good practice can be applied.

Introduction

The punch is a fundamental human action that has shaped our collective evolution (Carrier, 2011). From the shape of our faces (Carrier & Morgan, 2014), to the development of our opposable thumbs (Morgan & Carrier, 2013), the closed fist used to strike an adversary can be seen as one of the many defining actions of humanity. As established by van Bottenburg and Heilbron (2006), the punch and similar violent actions have been shaped by "sportification" as the culture of the world has shifted in modern times. This transformation of human combat into combat sports, through sportification, has provided a platform to better understand the fundamental action of punching through the lens of the performance driven sport sciences (Burwitz, Moore, & Wilkinson, 1994).

Investigations into the biomechanics of the punch have largely been quantitative in nature, exploring kinetics (Atha et al., 1985; Walilko et al., 2005; Walker, 1975), and kinematics (Girodet et al., 2005; VencesBrito et al., 2011) at a fundamental level. Qualitative investigations of combat sports have been scarce (Reider, 2004; Spencer, 2009), with even fewer studies exploring the knowledge of expert coaches to develop a holistic understanding of punching (Halperin, Chapman, Martin, Lewthwaite, & Wulf, 2016).This paucity of knowledge stands out, as similar works can be found in other sports (Jones, Bezodis, & Thompson, 2009; Thompson, Bezodis, & Jones, 2009). This manuscript aims to determine key characteristics of effective punching through the thematic interviewing of experienced boxing coaches, a method popular in sport coaching research (Jones, Armour, & Portrac, 2003). The findings of this qualitative work will be compared to current quantitative findings in the biomechanical analysis of punching. Boxing coaches were chosen for this analysis, as it is a combat sport that focuses solely on punches to the head and body. We theorise that this focus should produce greater technical proficiency due to the constraints of the sport (Renshaw, Chow, Davids, & Hammond, 2010). Through the above method of triangulation, a better understanding of the technical elements of the punch will be developed and areas of further research will be highlighted. The findings from this study will inform future biomechanical analyses of the punch, where coaches' knowledge can be adapted into biomechanical variables that can be analysed in future research. This will provide a greater comprehension of punching both in the sporting context and as a fundamental human movement.

Methods

Participants

A convenience sample of five New Zealand based professional and amateur boxing coaches were interviewed for this study. Due to the sampling method of this study, several of the coaches did not meet the strict criteria of being expert coaches as proposed by Cote et al. (1995). At the time of the interviews, the coaches all had at least ten plus years of coaching experience. Of the sample, four were certified amateur coaches (certified by the International Boxing Association) and one was a professional boxing coach. All of the coaches had trained national level champions at the amateur level. Four of the five coaches had trained fighters that had competed at the elite international level, three of the amateur coaches and the professional coach. Three of the coaches (all amateur) had worked with national boxing programs abroad and in New Zealand. At the time of the interviews, all coaches were active in the training of competitive boxers.

Data collection and analysis

Semi-structured, in-depth interviews were conducted with each coach to determine key technical features for an effective punch. As per Patton (2002), follow-up questions and detailed-oriented probes were used to clarify the meaning of the responses given. The interviews were separated into two sections, an introductory section exploring the coaches' history in the sport, and a technical section focused on the specifics of what they deem an "ideal punch". The introduction section was primarily used in this study to improve the communication between the coaches and the interviewer (Patton, 2002). Findings from this section were not included in this manuscript due to their non-relevance regarding the research question. The results of the second section were used in the analysis. These questions were focused on exploring coaches' knowledge through multiple sensory pathways, i.e. questions were asked about how landing a punch felt, what it looked like, and what it sounded like (Coté et al., 1995). The interviews took approximately 45 to 80 minutes to complete depending on the individual coach's willingness to expand on topics and their general talkativeness. Despite the variation in the length of interviews, it was made certain that the key topics were discussed in adequate depth.

The interviews were all digitally recorded and then transcribed verbatim by the primary investigator. During the transcription process, all identifying information was scrubbed to maintain anonymity of the coaches. In line with similar studies (Jones et al., 2009; Thompson et al., 2009) thematic content analysis was used to analyse the interviews. This was achieved by using a constant comparative method that involved the collation of raw data into themes, reaching a point where no new information or themes could be observed (i.e. data saturation)(Strauss & Corbin, 1998). In the initial stage of analysis, themes were identified that required further investigation. This involved dividing the text, based on the repetition into themes that were related to the topic in question (i.e. what coaches considered to be important aspects of a good punch) (Kronberger & Wagner, 2000). The content of these themes were subject to an extensive search of the interview text for commonalities and repetition of key words, which were then categorised (Jones et al., 2009). This resulted in first and second order themes being established. A first order theme was established if it met the criteria of being discussed most frequently by all five coaches in relation to effective punching. Subsequently, themes were classified as being second order when at least three of the coaches discussed it.

To cultivate trustworthiness and enhance credibility, a second peer reviewer was employed to theme the transcripts in parallel with the primary investigator (Côté, Salmela, Baria, & Russell, 1993). After sentence-by-sentence open coding (Coté et al., 1995), the two reviewers met to discuss their findings and find agreement on incongruent findings. Finally, triangulation of the qualitative findings was performed with an expert reviewer (Marshall & Rossman, 2014), who debriefed the investigator and helped refine the final themes. As in similar studies, analysis was an iterative process where concepts were subject to continual evaluation. As a result confidence in the concepts' validity was developed (Jones et al., 2009; Thompson et al., 2009).

Results

The results in this section were focused on the coaches' technical analysis of effective punching. This section was constructed from first order themes identified, and expanded with frequent terms and quotes. In an effort to avoid authorial bias, the findings are presented as given by the coaches, with no reference to the current literature regarding punching biomechanics. Triangulation between the findings in this section and the current literature was performed in the discussion (Marshall & Rossman, 2014). There was a consensus among the five coaches interviewed as to the key elements of effective punching. The four first order themes identified from this consensus were: 1) "whole body movement", 2) "footwork", 3) "hip and shoulder rotation", and 4) "hand and arm position".

Whole Body Movement

Coach 1 (C1): "You might be able to throw a jab without taking a forward movement, like a static punch, but it's never going to be as effective as if you've timed it with your foot work. Stepped in with a shot."

C4: "...you got to put the body weight in behind the punch, and you effectively try and stab the person with your punch."

A concept identified by all of the coaches interviewed was that when punching for optimal force, rather than strategic use (Walsh, 1951), a boxer needs to move their entire body weight forward, into the target in a fluid manner. This concept was found to be interrelated with the higher-order themes of "footwork" and "hip and shoulder rotation". "Whole body movement" differed from the inter-related themes in that the coaches explained the other themes could be used in a variety of circumstances, while "whole body movement" was used in attacking actions. The coaches spoke of "body weight/weight of the body" moving forward in a "fluid' and "in sync" manner. The coaches pointed out flawed technique as the opposite of this. Using the term "arm punches" they identified a lack of body movement when punching, instead these poor technique punches relied on the strength of the arm to produce force; a sub-optimal strategy for forceful striking. In the context of the sub-optimal arm punching example, "whole body movement" is the concept of summating the mass and muscles of the body to produce greater force during impact (Dempsey, 1950).

Footwork

C2: "Most of the force is generated from the legs. From the feet up."

C3: "...the force, the weight of the body behind the shot, you know it's stated that at least 70% of the force in the punch comes from below the waist line..."

The concept of "footwork" in effective punching was separated into two components by all of the coaches interviewed, "balance" and "pushing" off of the feet. "Balance" was described similarly to the concept of balance as understood in the literature, the ability to maintain equilibrium under explicit conditions (Gamble, 2012). Specific to boxing, the maintenance of balance was explained as the need to, "Step with a punch. One punch, one step." (C1). The relationship to "whole body movement" is clear here, but with the additional focus of remaining "stable" and "balanced" for continuing attacks and to avoid leaving the boxer vulnerable to "counter attack".

"Pushing" off the feet was clearly identified by all coaches as the key to producing punching force. There was variability in the exact description of the ideal technique used when "pushing" off the feet. Several coaches referred to a "push" from the feet to propel a step (two coaches), while others a "push" to "rotate the heel" laterally (two coaches), while one coach thought of the push more linearly, a drive forward into the target at impact. This variability could be a result of differences in the actual technique instructed by the coaches, or could be a simple semantic disagreement. Regardless, the concept identified by all coaches was that the foot "push" was the key to producing effective punching force. Moreover, when asked for a principal coaching cue to give to a boxer for the improvement of punching force, all coaches provided the same answer, identifying "footwork" as that cue above all others.

Hip and shoulder rotation

C1: "I personally think that you'll be seeing the guys that get full rotation of the hips will land the better shots."

C3: “…so if you don’t use a rotation, that is you don’t rotate your body, so that both hip and shoulders come around behind the shot, then it is only an arm punch.”

Rotation of the hips and shoulders during punching was identified as crucial to effective punching by the coaches interviewed. The concept was explained as a rotation of the hip and shoulder towards the intended target. For example, if throwing a rear hand right punch, the right hip and the right shoulder would rotate towards the target. This combined with a step or “push” from the lower body’s “footwork” were the two primary components of the “whole body movement” theme. Not only moving the body forward, but bringing more of the body into play and avoiding “arm punches”. This movement was also recognized by the coaches as initiated by a “push” from the feet used to rotate the hip around, followed by the shoulder, and finally the hand.

C5: “So it’s a build-up and then a completion, in a timed manner which will equate to strong force at a certain point.”

The explanation of the rotation was crutched around the idea that a boxer must be careful not to over rotate, putting themselves in a dangerous position, echoing the concept of “balance” in the above sub-section.

Hand and arm position

C4: “Where the punch comes from is as probably important from a defensive perspective, because if you are throwing arm punches from your shoulders or your hips, it’s clearly not from your face, so you are going to get f***ing caught sooner or later.”

C5: “Bad technique when they’re not bring their shoulder up to protect their chin and give more power to the punch…”

The positioning of the hand and arm as indicated by the coaches was broken down into two primary concepts. A defensive focus on using the hand and arm to protect the boxer and a focus on striking with correct hand position to maximize force.

Specific to defence, the coaches spoke to a need to “avoid dropping their hands”. Keeping the “hands up” allows a boxer to “catch” incoming punches with the hands and bring the arms up to "guard" against incoming punches (Slack, 2012). The positioning of the hands and arm for defence can be conceptualized as both an intermediate component of punching, important before and after strikes are thrown, and an active part of a punch to protect the boxer in the case when both fighters are punching simultaneously (Slack, 2012).

Hand position was described by the coaches as a combination of hand elevation in relation to the elbow and a rotation of the hand moments before impact. Elevation of the hand was simply described as follows, "Your hand must be above your elbow" (C3), and was explained to be one way to allow for the hand to "turn over" pre-impact. This was clarified in that this point was only for punches in a horizontal attack (straight punches and hooks), not for vertical strikes (uppercuts).

"Turning the hand over" was identified by C4 as actively "pronating the hand" during the punch. The coach (C4) stated that by performing this action a boxer can "get a bit more extra reach", and as stated by another coach, is active in "pulling your shoulder around" (C3). This statement links the hand to shoulder rotation, and thus, "whole body movement".

Discussion

The aim of this study was to determine key attributes in effective punching through thematic interviewing of experienced coaches. The results of the interviews performed found congruency in the coaches understanding of efficacious punching. The experienced coaches identified four principal components that produce effective punches: 1) whole body movement; 2) footwork; 3) hip and shoulder rotation; 4) hand and arm position. Conflicting reports were evident in the coaches' exact descriptions of the actions of punching within the principle components, but the thematic consensus found does allow for triangulation of the data with literature on the topic. The following is a synthesis of the interview findings and a triangulation of those findings with the current literature on the topic.

A hierarchy of the first order themes (principle components of effective punching) was identified through the analysis of the interview data obtained from the study participants. Effective punching was structured hierarchically under the umbrella of the “whole body movement” theme. The themes of “footwork”, “hip and shoulder rotation”, and “hand and arm position” all combined to produce the body movement assigned by the coaches to produce effective punching. Furthermore, under the “whole body movement” umbrella a clear hierarchy was also identifiable. “Footwork” was clearly indicated by all coaches as the starting point, propelling the body forward, and dominant component in executing “whole body movement”, for example, initiating the torque used to rotate the hip and shoulder. Proper “footwork” does this in a manner facilitating balance, permitting continued attacks or defensive actions. Initiated and produced by “footwork”, the hip rotation continues up the kinetic chain producing shoulder rotation as explained by the coaches. The shoulder rotation in turn effects and is affected by the movement of the arms. When positioned correctly, the arm and hand enable the continuation of the shoulder rotation and application of force into the target. A foot to hand movement bringing the entirety of the body into a single application of force.

The current literature exploring punching echoes much of that identified by the experienced coaches. Regarding “whole body movement”, Neto et al. (2007) found effective mass to be crucial to effective punching. The concept of effective mass in combat sports has been simplified in earlier works as a calculation of the inertial contribution of the fighter in a punch (Lenetsky et al., 2015). As such, it is likely that the greater “whole body movement”, the greater the inertial contribution; the greater the inertial contribution, the greater the effective mass; the greater the effective mass, the more effective the strike. McGill et al. (2010), first theorized that specific muscular adaptation, which result in reducing compliance in the musculoskeletal system, leads to increases in effective mass. There is a conflicting theory, arguing that effective mass is heavily influenced by the drive from the lower body during impact (Lenetsky et al., 2015). The lower body drive theory is affirmed by the coaches’ insight; however, further research is required to confirm these findings.

Cesari and Bertucco (2008) identified several findings in their study of novice and expert karate practitioners (karateka) that linked effective punching to the “whole body movement” theme. The authors found that beyond greater punch impulse, expert karateka potentially had more anterior displacement of their centre of pressure (COP) than novice practitioners (a non-significant finding) and that the experts had greater upper limb displacement during the punch. The authors suggest that the upper limb displacement was used to commit an "extra amount of upper limb mass" to the impact.

Continuing down the hierarchy of effective punching, "footwork", specifically "pushing" with footwork, was investigated by Filimonov and colleagues (1983) who found greater contribution from the lower body in experienced boxers and those indicated to be stronger punchers. Loturco et al. (2014), reinforced the importance of "pushing" with footwork with their linking of punch acceleration to propulsive power during jump squat testing (r=.80) in karateka. The propulsive power of the jump squat had the highest correlation of all measures including, upper body power measures and lower and upper body strength measures. More recently, Loturco et al. (2015), performed a similar study on experienced boxers and found similar results (r=.85) when comparing mean propulsive power in jump squats to punching impact force. Training studies have found that increases in maximal strength (both lower and upper) produce statistically meaningful increases in punching force, 12.4-21.1%. Due to the limited literature at the time, Lenetsky et al. (2013) reviewed movements similar to punching to provide insight in a review of contributors to punching impact kinetics. Their findings further reinforce those above and those indicated by the coaches interviewed. Of note, the authors bring attention the findings of Stodden et al. (2006), whom found a boxing specific contralateral step increased ball speed when compared to a static throw. A step much like the one proposed by C1 above.

Due to limited research investigating coaches' knowledge of the punch, specifically "balance" in relation to "footwork" when punching, it is difficult to draw parallels to any existing research. However, a single study showed that experienced karateka undertook less of a COP shift backwards after impact when compared with novice practitioners (Cesari & Bertucco, 2008). This finding supports coaches' reports from the current study with the concept of "balance" being used to facilitate continued attack. A shift backwards would necessitate a return to the forward position before any additional attacks could occur. As a whole, the literature relating to "pushing" and "balance" serve as strong evidence confirming the importance of "footwork" for effective punching as stated by our cohort of experienced coaches.

The current study highlighted a current gap in research around "hip and shoulder rotation" in punching as described by the coaching cohort in this study. Of those explored, there were no comparative studies of different levels of combat sport athlete or training studies found. In one of the few descriptive studies found, "hip and shoulder rotation" was defined as a method of transferring the forces produced by the lower body up the kinetic chain and into the target (Tong-Iam & Lawsirirat, 2016). An analysis of a European boxing champion highlights this transfer, as velocity measures at the hip, trunk, and arm increased up the kinetic chain as punching movements were executed (hip = 765.19°.S^{-1} ± 29.49, trunk = 866.69°.S^{-1} ± 42.54, arm = 1404°.S^{-1} ± 102.23) (Cabral et al., 2010). In addition to a method of summating velocity, the limited literature also reinforces the concept of "hip and shoulder rotation" as a strategy used to shift a combat sport athlete's weight forward into a target. Cheraghi et al. (2014) postulated that their findings of anterior hip displacement in amateur boxers were used to shift the fighters body weight forward, into the target.

With the paucity of literature relating to "hip and shoulder rotation", it is not possible to link the coaches' expert knowledge to scientific findings as clearly as done with the theme of "footwork". However, this has highlighted potential links that future research should investigate.

The positioning of the hand and arm as explained by the coaches is supported by the literature regarding offensive actions. 3D kinematics of straight and hook punches found an elevation of the wrist above the elbow as described by the coaches (Whiting et al., 1988). In conjunction with the elevated wrist, Morita et al. (2011), pinpointed a rotation of the wrist in the same plane as again explained by the experienced coaches. Much like the "hip and shoulder rotation" literature, no research was found that compared "good" and "bad" kinematics in relation to the variables provided by the coaches. As such, only the few descriptive studies found were used for triangulation. No literature was discovered exploring the kinematics of defensive actions using "hand and arm position" in combat sports. The importance of such defensive actions has been well established in boxing specific writing (Dempsey, 1950; Lee, 1975; Slack, 2012). Still, the lack of peer reviewed literature in relation to our findings from the thematic interviews stands out as another gap in the literature that needs examination in future studies.

The triangulation of the findings from the coaches' interviews with the current information available from combat sport literature clarifies many of the themes identified, and serves to highlight current gaps in knowledge. Combining the themes found in the current study and findings in the literature serve to breakdown punching from a "whole body movement", to a combination of footwork, enabling proper rotation, finally leading to a properly thrown hand landing on target. The paramount importance of footwork was identified as the initiator of the punch, rotation, and potentially a key in transmitting greater inertia during impact. The themes of "hip and shoulder rotation" and "hand and arm position" were connected to kinematic findings, although, the paucity of experimental research in the area leaves much to be understood as to the exact technique needed to maximize punching performance. Specific gaps in the literature found through our triangulation include: a further understanding of "footwork" in the initiation of punching actions; the role of the lower body during impact; the relationship of hip velocity to punching kinetics; the kinematic impact of "turning the hand over" while punching; and, the precise kinematics of effective defensive using the hand and arm position.

Conclusion

The main aim of this study was to determine key characteristics of effective punching as considered by expert coaches. From the interview data collated, coaches in this investigation universally agreed on the key themes of effective punching as, "whole body movement", "footwork", "hip and shoulder rotation", and "hand and arm position". These first order themes were supported by the literature via triangulation. Many of the second order themes were also triangulated with the current research. "Pushing" off with the legs, maintaining "balance", rotating the hips and shoulders, keeping the hands elevated, and "turning the hand over" were all supported with quantifiable data. Second order themes highlight gaps in the literature. These gaps being the details of the lower body's role in initiating the punch, the role of the lower body during impact, and the kinematic impact of the hip, shoulder, arm, and the hand in effective punching. While there was agreement in the general themes, there were exact technique cues presented by individual coaches that did not have agreement within the cohort. These disagreements, interestingly, fell primarily within the unsubstantiated second order themes. Such results guide the way for future chapters in the thesis, specifically in terms of developing research that gives voice to experiential data of expert coaches, where this data can be used in conjunction with current theory to enhance knowledge in the area of effective punching in combat sports.

Acknowledgements

The authors would like to thank the invaluable guidance and mentorship of Dr. Tony Oldham in the writing of this manuscript. Dr. Oldham's efforts in education is inspirational and counting him is a colleague and friend is an honour. We would also like to thank the coaches interviewed for their time and contribution to the manuscript. They took valuable time out of their schedule to provide us with their expertise which we are grateful for.

Section 2:
Measures of impact kinetics

CHAPTER 5

A PRACTICAL METHOD FOR THE MEASUREMENT OF STRIKING IMPACT KINETICS VIA ACCELEROMETERY AND INERTIAL MODELLING

Reference

Lenetsky, S., Nates, R.J., Brughelli, M., & Schoustra, A. (2017). A practical method for the measurement of striking impact kinetics via accelerometery and inertial modelling. *Journal of Sport Science*, In prep.

Author contribution

SL: 80%, RJN: 10%, MB: 5%, AS: 5%

Preface

Chapter five explores the development of a novel method to measure impact kinetics in combat sports, and establishes the validity and reliability of the new method. This chapter is a necessity for the analysis of impact kinetics used in later chapters.

Abstract

The kinetics of striking impacts have been explored repeatedly in combat sports related literature due to the key role impact has in the performance of full contact combat sports. The majority of devices used in the literature require intricate equipment and many of the dynamometers used fail to realistically reflect the inertial characteristics of human targets and training equipment. This study implemented a novel and simple method of measuring impact kinetics using a target developed to be like those seen in combat sports, a commercially available striking bag. Using the commercially available striking bag with the addition of a triaxial accelerometer; impulse, peak force, rate of force development, and mean force were determined. Reliability and validity statistics were obtained from multiple impacts with a custom, mass adjustable, ballistic pendulum. Reliability calculations determined that all measures had acceptable reliability (CV $\leq$ 4.6%). Using linear regression modelling, the coefficient of determination scores displayed a good fit for the model ($r^2 \geq 0.92$) for all variables except for rate of

force development ($r^2 = 0.57$), when comparing the spectrum of masses used on the pendulum to the dependant variables. Percent change in mean scores revealed that two initial impacts are needed to compress the bag to a point where the compliant material produces repeatable readings. This novel method represents a reliable and valid approach to measuring striking impact kinetics and is easily adaptable to specific types of hanging striking target.

Introduction

The measurement of striking (punches, kicks, elbows and knees) impact kinetics has been explored substantially in combat sports literature (Atha et al., 1985; Busko et al., 2014; Chadli, Ababou, & Ababou, 2014; Falco et al., 2009; Fanning, 2011; Fortin et al., 1995; P. Girodet et al., 2005; Liu et al., 2014; J. Mack et al., 2010; Neto et al., 2012; Nien, Chuang, & Chung, 2004; Pedzich, Mastalerz, & Urbanik, 2006; Pierce et al., 2006; Pieter & Pieter, 1994; Smith et al., 2000; Vos & Binkhorst, 1966; Walilko et al., 2005). There are discrepancies in the literature regarding the specific factors (muscle activation patterns, the role of the lower body, and ideal training stimulus) that result in effective impact kinetics (Lenetsky et al., 2015). Still, it has been recognised that in general impact kinetics play a key role in the performance of full contact combat sports athletes (Lenetsky et al., 2013).

The methods of measuring impact kinetics vary throughout the literature. The most common designs include: force plates or load cells (Atha et al., 1985; Falco et al., 2009; Fanning, 2011; Girodet et al., 2005; Mack et al., 2010; Neto et al., 2012; Pedzich et al., 2006; Pierce et al., 2006; Smith et al., 2000), fluid filled targets (Fortin et al., 1995; Pieter & Pieter, 1994), strain gauges (Chadli et al., 2014; Vos & Binkhorst, 1966), and accelerometers inserted internally in striking targets (Busko et al., 2014; Nien et al., 2004; Walilko et al., 2005). These dynamometers typically require expensive and complicated equipment to achieve measurement, with acceptable reliability and validity (Busko et al., 2014; Liu et al., 2014; Smith et al., 2000).

An important concept neglected by much of the current research is the interaction between the striking target and the striker. The use of striking dynamometers on immovable (or very rigid) surfaces or objects, commonly seen in the literature

(Falco et al., 2009; Fanning, 2011; Pedzich et al., 2006; Smith et al., 2000), potentially fails to reflect the inertial characteristics of a human target and may produce results that are specific to striking very rigid targets only. The movement of a rigid target is negligible and therefore the time of contact is very small. While a human target (or training bag) will move significantly during contact, meaning that there is much more time available during the contact. This will produce very different force profiles between the two. Also, the technique of the striking action would be quite different as a result of a highly rigid target. To avoid introducing such potential error some researchers have used load cells attached to inertially relevant pendulums (Atha et al., 1985; Chadli et al., 2014; Neto et al., 2012) (i.e. similar mass to a human or human segment), while others have altered tools used by combat sports athletes regularly such as punching bags or human analogues to measure striking kinetics (Fortin et al., 1995; Girodet et al., 2005; Mack et al., 2010; Nien et al., 2004; Pieter & Pieter, 1994; Walilko et al., 2005).

Studies using these inertially relevant targets produce results which theoretically should reflect the actual competition performance of their participants; yet there is still considerable variability in the findings exploring impact kinetics. For example, in the measurement of punching kinetics, outputs have varied in peak punching force from 1745N to 6320N (J. Atha et al., 1985; Girodet et al., 2005). Pieter and Pieter (1994), point out that differing striking protocols and athletes can explain some of the difficulty in comparing outputs between these studies. Furthermore, Pedzich et al. (2006) and Busko et al. (2014) argue that due to the variation of the target size and protective padding on the multitude of striking dynamometers used in the literature, accurate comparisons of findings are difficult. In a review of the literature we were unable to find any studies that did not in some way pad the impact target, the striking limb, or both. This makes instinctive sense; a full strength bare knuckle punch, in this example, against an unpadded target would most likely result in injury. Thus, striking dynamometers have been designed in such a way that, while minimizing injury risk, does not accurately measure the true impact kinetics. Some force will always be absorbed by the protective padding during impact, and the time period of the impact varies due to that absorption. This inherent limitation of the above striking dynamometers does not mean that measuring impact kinetics in combat sports is meaningless. Rather, in agreement with Busko et al. (2014), we believe that further research must avoid comparison between striking dynamometers as seen previously in the literature (Lenetsky et al., 2013). We argue the striking dynamometry, like that found in the literature, need only be: 1) reliable within the device used; and 2) valid in the ability to differentiate kinetic magnitudes to identify differences between participants, and within participants over time. In summary, a striking dynamometer must produce reproducible results that should only be compared to other results from that same dynamometer, reliability and internal validity.

The aim of this study was to develop a novel, and simple method to measure impact kinetics from a device that is inertially similar to the targets of combat sports. The measurement of these kinetic results can in turn be used to optimize striking performance in combat sports athletes. To accomplish this, we inertially modelled a commercially available punching bag and mounted an accelerometer to the outside of that bag; allowing for the measurement of kinetic variables, without the modification of either piece of equipment. To establish reliability and internal validity we struck the equipped punching bag with a spectrum of loads using a variable mass ballistic pendulum. A comparison of the measured kinetic variables to the pendulum mass was performed to establish validity and multiple strikes where performed to establish reliability.

Inertial modelling of striking bag

This research required the measurement of the instantaneous striking force during the impact period. To do so, an accelerometer was fitted to a striking bag. To convert the accelerometer data to instantaneous force a mathematical model was developed in which a striking bag was simulated to be a compound pendulum. Referring to Figure 4, the pendulum has a centre of gravity at "C" and pivots around position "*O*", which is the suspension point. The target striking zone "T" was placed central on the bag to provide a clear and relevant point of impact for future athletes. The accelerometer was positioned at "*A*".

The model applies Newton's Law of Motion to the striking bag accelerating around the pivot "*O*" due to the striking force at "*T*". The rotational inertia of the bag (around the pivot "*O*") resists the striking force and determines the angular (rotational) acceleration of the bag. With reference to figure 4, the following are used for values and variables used in the derivation of the model:

$\overline{OA}$ the distance from the accelerometer to the pivot point (m).

$\overline{OC}$ the distance from the centre of gravity to the pivot point (m).

$\overline{OT}$ the distance from the point of impact to the pivot point (m).

$\vec{\alpha}$ the angular acceleration of the bag around the pivot in rad/s^2.

$\vec{a}$ the linear acceleration measured at the accelerometer in m/ s^2.

$\vec{F}$ the force of the punch thrown by the boxer at the impact point in N.

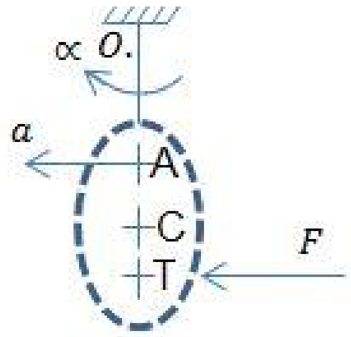


Figure 4. A graphical representation of the key variables.

The model assumes that the striking force "F" is horizontal. As such, the model will deliver only the horizontal component of a strike.

The objective of the model development is to determine a mathematical relationship between the instantaneous measured acceleration from the accelerometer and the instantaneous striking force.

The force (of the strike) on the bag produces a moment ($\vec{M}$) on the bag around the pivot point where it is hung. This moment causes the angular acceleration of the bag around the pivot. Newton's Law of motion equates the resultant moment to the acceleration (of the bag around the pivot, as shown in Equation 5 (Young, Freedman, & Bhathal, 2011):

Equation 5

$$\sum \vec{M} = I\vec{\alpha}$$

"I" is the rotational inertia of the bag around the pivot point and "$\vec{\alpha}$" is the angular acceleration of the bag around the pivot point. The "sum of" in the equation is for the general case where there may be many moments acting on the system, in this case, there is only one moment ($\vec{M}$) on the bag is due to the force applied by the strike.

From figure 4, it seen that the moment due to the strike is the force acting at the distance $\overline{OT}$, as shown in Equation 6:

Equation 6

$$\vec{M} = \vec{F}\overline{OT}$$

Equating 5 and 6, results in Equation 7:

Equation 7

$$\therefore \vec{F}\overline{OT} = I\vec{\alpha}$$

Now, the angular acceleration can be determined from the instantaneous linear acceleration measured by the accelerometer and knowing the distance of the accelerometer to the pivot point (Equation 8):

Equation 8

$$\vec{\alpha} = \frac{\vec{a}}{\overline{OA}}$$

In order to further develop equation 7, it is necessary to determine the rotational inertia of the bag around the pivot point "I". To do so, the physical relationship between pendulum characteristics and its natural frequency were used. The standard equation for the natural frequency of a compound pendulum may be applied to the bag in Equation 9.

Equation 9

$$\omega_n = \sqrt{\frac{mg\overline{OC}}{I_P}}$$

In this formula (Young et al., 2011):
ω_n the circular frequency of the compound pendulum in rad/s.
I_P the moment of inertia of the compound pendulum in kgm^2.

The circular frequency is determined in Equation 10 from the actual frequency (f) of the bag as it is made to swing (with small amplitudes).

Equation 10

$$\omega_n = 2\pi f$$

Combining these two equations gives Equation 11:

Equation 11

$$\therefore I_P = \frac{mg\overline{OC}}{(2\pi f)^2}$$

The force can now be calculated by combining equations 5, 6, and 7 to produce Equation 12.

Equation 12

$$\vec{F} = \frac{mg\vec{a}\overline{OC}}{\overline{OT}(2\pi f)^2\overline{OA}}$$

The tangential component of $\vec{a}$ will be used as the bag pivots primarily around the horizontal axis and any radial stretching of the bag will be neglected. That means $\vec{a}$ will be replaced by $\vec{a}_{Tan.}$ (Equation 13).

Equation 13

$$\therefore \vec{F}_{Tan.} = \frac{m\ g\ \overline{OC}\ \vec{a}_{Tan}}{\overline{OT}\ (2\pi f)^2\ \overline{OA}}$$

The above equation will give the instantaneous impact force as a function of instantaneous acceleration as recorded by the accelerometer during the period of impact. In Equation 13, mass (m) was determined through weighing the striking bag. The frequency of the bag was found by counting the oscillations of the bag over one minute after a small perturbation. The centre of gravity (C) was found by placing the bag on a flat crosspiece, the same length as the bag, which was placed on a fulcrum. The plank was then adjusted until a balance point was found, identifying the centre of gravity. The accelerometer (A) was attached to the back surface of the bag, directly opposite to the impact target. This specific position was chosen because it was found from preliminary tests that other positions (i.e. top, bottom, and next to the target signal) resulted in significant signal noise due to transverse vibration of the bag during impact.

Following Equation 13, the value of $\vec{a}_{Tan}$ needs to be found from the accelerometer signal. As the accelerometer is mounted in a specific position, but arbitrary orientation, it is first necessary to determine the orientation of the accelerometer. This is done by measuring the three components of acceleration from the triaxial accelerometer when the bag is stationary (i.e. before impact).

This signal (when stationary) comprises of three components designated b_x, b_y, b_z, the combination of which produce the resultant vertical acceleration of gravity (g = 9.81 m/s²). This is used as a calibration of magnitude, as well as orientation in Equation 14:

Equation 14

$$|b| = \sqrt{{b_x}^2 + {b_y}^2 + {b_z}^2}$$

In this formula:

$|b|$ is the magnitude of vector $\vec{b}$.

To calibrate, Ψ is a correction factor applied to all signals to ensure that $|b|$ equals exactly 1g. Calculated in Equation 15:

Equation 15

$$g = \Psi|b|$$

$$\therefore \Psi = \frac{g}{|b|}$$

During impact, it is necessary to remove the force of gravity from the accelerometer data. The triaxial accelerometer signal during impact is designated as $\vec{a}$ where (Equation 16):

Equation 16

$$|a| = \sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2}$$

The angle between $\vec{a}$ and $\vec{b}$ also needs to be determined in order to remove gravity through Equation 17. The angle between the two vectors is:

Equation 17

$$\theta = \cos^{-1}\frac{\vec{a}\cdot\vec{b}}{|a||b|}$$

This is the angle between $\vec{a}$ and the vertical.

Where from the standard vector calculation is Equation 18:

Equation 18

$$\vec{a} \cdot \vec{b} = a_x b_x + a_y b_y + a_z b_z$$

With the angle of the accelerometer found, the tangential acceleration can be calculated in Equation 19 and the variables can be seen in Figure 5:

Equation 19

$$\vec{a}_{Tan} = \sqrt{(|a|\Psi \cos\theta - |b|\Psi)^2 + (|a|\Psi \sin\theta)^2}$$

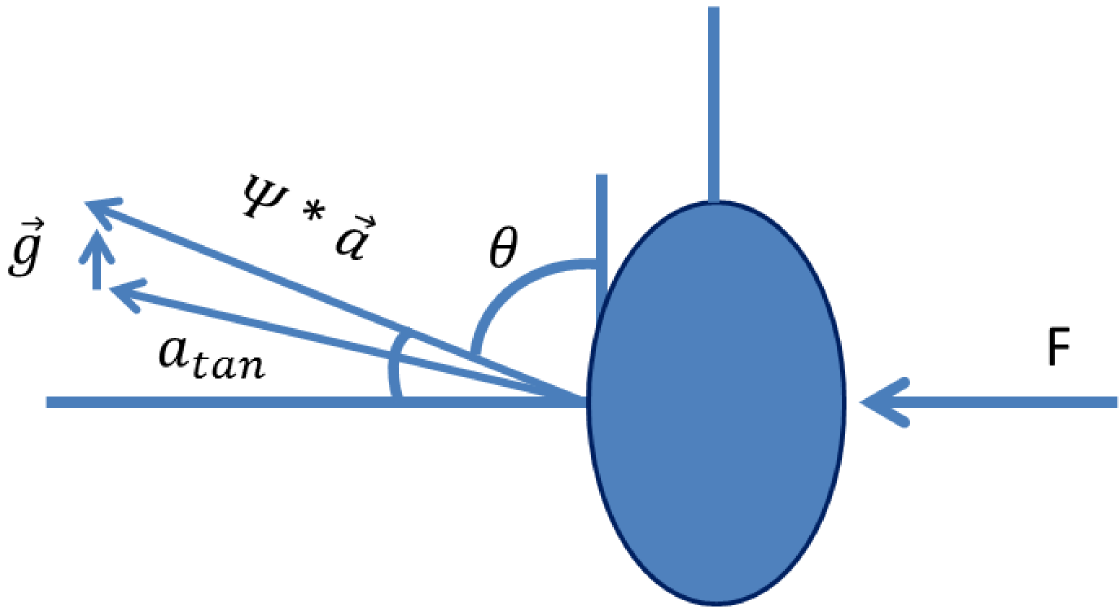


Figure 5. Visualisation of Equation 19.

Equations 7 and 8 were combined, and together with the recording of the accelerometer signal, the instantaneous kinetics were calculated during the impact period (defined in the results section). From this force versus time trace, other parameters were determined as follows:

- **Peak force**
- **Mean force** over the impact period
- **Rate of force development** from the beginning of the impact to the point of peak force (in units of Newton per second)
- **Impulse** in units of N*s found by integrating the instantaneous force over the impact period where: $Impulse = \int F dt$

Methods

Equipment

The striking impact dynamometer developed for this study was comprised of a commercially available striking bag (NZ Boxer™, Teardrop style, Auckland, New Zealand) and a wireless triaxial accelerometer (I Measure U Ltd., Auckland, New Zealand). The teardrop bag had a mass of 24.6kg and had a length of 1m. The accelerometer sampled at 1000Hz and had a maximal acceleration reading of 16 times Earth's gravity. A custom built ballistic pendulum was designed to produce a very repeatable and controllable impact on the striking dynamometer. This pendulum was designed to be very ridged and consisted of two parallel, very light cables (<100g) fitted to a range of commercial dumbbells (Hammer Strength™, Cincinnati, OH, USA). The parallel wires were used to ensure that there was no rotation of the dumbbell during the swing. The pendulum was raised to a height of 2.05m for each test impact, loaded with a range of masses to produce a spectrum of impact forces. The masses tested were, 10.8, 12.46, 14.46, 16.4, 18.34, 26.22, 30.4, and 34.5kg. A custom-built LabVIEW program (Version 11.0, National Instruments Corp., Austin, TX, USA) was used to analyse the accelerometer data and calculate the force kinetics.

Study design

To develop data for analysis the ballistic pendulum was used to impact against the equipped striking bag. For each pendulum mass, six repeated trials were performed to calculate reliability results. In addition, the multiple trials were implemented to explore the compliance of the bag to repeated impacts, the result of which may cause compression of the bag and its contents and hence variability in its response. Six trials were performed, as pilot testing indicated this number of trials would allow for proper reliability analysis post-compression. The bag was adjusted to return the contents to their initial state between each mass change. This was performed through manual shifting of the contents not effected by the impact, moving the bag filling back into the compressed areas. To establish internal validity of the equipped punching bag the varying masses were compared to the findings of the bag calculated through the custom LabVIEW program. A threshold of 400N was placed on the ending of the force curve for the calculation of impulse and mean force due to signal noise caused by the swing of the equipped bag after the impact period, as seen in Figure 6.

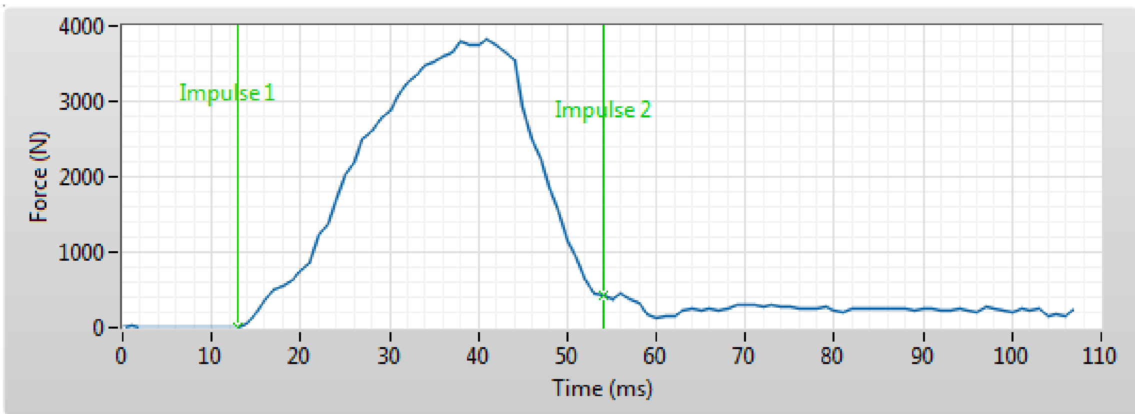


Figure 6. Output of the custom-made LabVIEW programme.
The vertical lines labelled "Impulse 1" and "Impulse 2" indicate the area used for analysis as per the protocol explained above.

The independent variable measured was the instantaneous acceleration of the accelerometer as a function of time. Dependant variables were peak, and mean force, impulse, and rate of force development. Peak and mean force were included due to common inclusion throughout the literature (Pierce et al., 2006; Smith et al., 2000; Walilko et al., 2005). Likewise, impulse was included as it has primarily been used in the literature to calculate the effective mass of strikes (Lenetsky et al., 2015). While rate of force development is a measure that has not previously been explored in combat sports literature, we chose to include this variable for analysis because: 1) it has been established that two impacts can have very different force-time curves but the same impulse (Halliday, Resnick, & Walker, 1997), and it allows for a greater understanding of the force-time curve without requiring full analysis; 2) Fowler and Lees (1998) state that greater loading rates are more injurious due to the viscoelastic nature of biological materials, this indicating strikes with high rate of force development would potentially be more damaging (a goal in full contact combat sports) (Lenetsky et al., 2013).

Statistical analysis

Mean and standard deviations (SD) were calculated for all dependent variables. All data were log-transformed for reliability statistics. Coefficient of variation (CV%) was calculated to establish the reliability of the dependent variables. Between trial percent mean change was calculated as well to explore the influence of repeated impacts. Reliability findings were calculated via a reliability spreadsheet *(xrely.xls)* from Sportsci.org (Hopkins, 2012b). Internal validity was examined using an analysis of validity by linear regression spreadsheet (*xvalid.xls)* (Hopkins, 2012a), analysing the data via linear regression and coefficient of determination. Both spreadsheets were based off of the works of Hopkins (Hopkins, 2000; Hopkins, Marshall, Batterham, & Hanin, 2009).

Results

A range of mean and standard deviation findings for all dependant variables can be found in Table 5. Between trial percent mean result for the equipped punching bag (Table 6) indicates that there was a levelling off process in the change in mean scores after the first two impacts on the bag in its initial state. Across all variables, the average percent difference in means between trials one and two was 6.9%, between trial two and three was 2.1%, and between three and four was 0.8% remaining consistent after that for all impacts.

Table 5. Mean and standard deviation results from the lowest and highest loads used in testing (10.8 and 34.5kg respectively).

Ballistic pendulum mass	Striking bag results
Impulse (N·s)	
10.8Kg	48.8 ± 1.3
34.5Kg	86.8 ± 1.8
Peak Force (N)	
10.8Kg	2261 ± 133.9
34.5Kg	3734 ± 323.5
Rate of Force Development (N· s^{-1}**)**	
10.8Kg	108050 ± 6864.6
34.5Kg	132299 ± 17153.6
Mean Force (N)	
10.8Kg	1376 ± 64.3
34.5Kg	2105 ± 124.2

Table 6. Between trial percent mean change.

	Trial 2 - 1	Trial 3 - 2	Trial 4 – 3	Trial 5 - 4	Trial 6 -5
Impulse	2.9	1.4	0.3	-0.2	-0.2
Peak Force	10.4	3.3	0.5	-0.8	0.4
Rate of Force Development	15.6	3.7	-0.2	-0.6	1.5
Mean Force	8.3	0.9	0.0	-0.9	0.6

.

Reliability (Table 7) displays that removing the first two of the impacts results in improved reliability.

Table 7. Reliability for the equipped punching bag.

6 Impacts

	CV
Impulse	0.9%
Peak Force	2.5%
Rate of Force Development	5.4%
Mean Force	2.6%

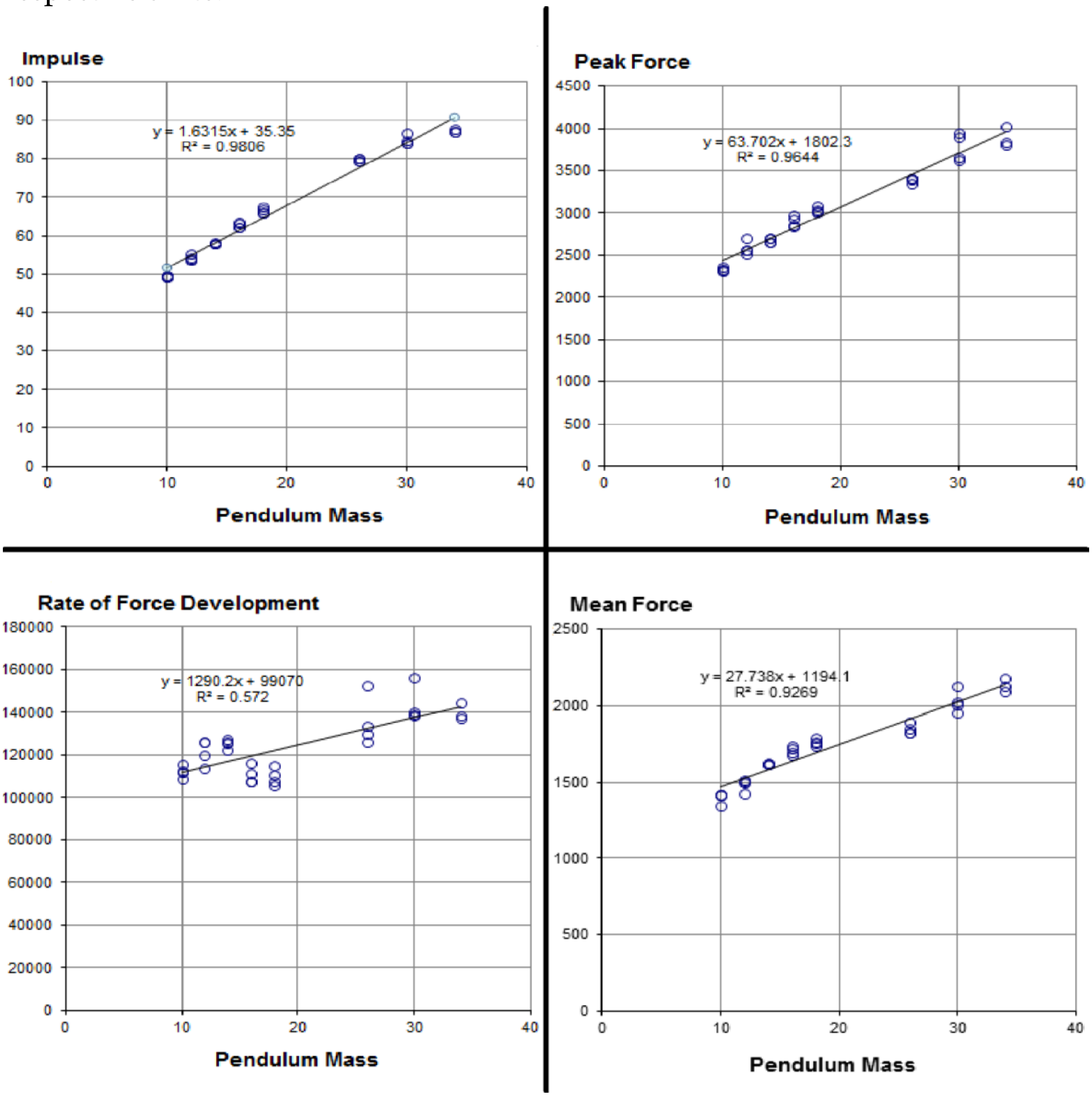
4 Impacts*

	CV
Impulse	1.0%
Peak Force	2.4%
Rate of Force Development	4.6%
Mean Force	2.2%

* = The first 2 compression influenced impacts were removed from the calculation

Internal validity testing comparing the dependent variables to the mass of the pendulum was found to have a good fit to linear regression models for all variables (impulse - $r^2 = 0.98$, peak force - $r^2 = 0.96$, and mean force - $r^2 = 0.93$), except for rate of force development ($r^2 = 0.57$). That is, the increases in pendulum mass resulted in increases in all dependent variables except for rate of force development. Linear regression figures, coefficient of determination, and regression equations can be found in Figure 7. The last four trials were used for this analysis as they were not influenced by the bag compression. There is slight variation in the findings found in Figure 7. This may be due to variations in the angle of impact, caused in part by a minor wobble that was inherent in the design of the ballistic pendulum.

Figure 7. Linear regressions comparing the pendulum mass and the dependent variables.
Pendulum mass is reported in kg, dependent variables are reported in their respective units.



Discussion

The purpose of this study was to develop a novel, and simple method of measuring striking impact kinetics. The method developed was proven ostensibly successful, requiring only a commercial teardrop bag and a triaxial accelerometer that can be attached without concern of orientation. This striking dynamometry approach has been found to produce reliable measurement of impulse, peak and mean force, and rate of force development across multiple impacts when struck with a ballistic pendulum. Additionally, this method is internally valid in differentiating magnitudes of impulse, peak and mean force across a spectrum of loads. Change in mean scores were found to appropriately illustrate the compressive nature of the equipped bag. On the specific striking bag used in this study it was found that two impacts were needed to compress the bag to a point where the compliant materials in the bag did not affect the majority of the readings. Other bags may require a greater or lesser number of impacts to reach a similar point. After an initial observation of this compression point using the above protocol, any similar striking bag can use this method. To our knowledge this is the first method using a working striking dynamometer with such simple, unaltered equipment. It is important to be aware that bags of longer length (i.e., more traditional heavy bags), will not produce similar results with this method. A longer bag will bend around the impact area and a less dense striking area would deform more significantly. Both of these changes in bags would cause greater error in the modelled assumption of a compound pendulum.

While a reliable measure across trials, rate of force development was not found to have a good relationship to the spread of pendulum masses tested. We believe this discrepancy is again due in part to the compressive nature of the striking bag and the differing size of the dumbbells used with the pendulum. The dumbbells increased in size non-linearly with the increase in mass. This may have resulted in the spread of rate of force development findings when compared to the pendulum mass. Additionally, the pendulum itself may have caused the issue with rate of force development. The ballistic nature of the pendulum is inherently limited in its ability to accurately reflect strikes in humans. For example, it has been proposed that additional force is applied during the moment of impact by combat sports athletes (Lenetsky et al., 2015). There is no additional force during the impact of the pendulum, only the momentum of the pendulum, where initial velocity and the mass of the pendulum determine the measure of rate of force development, a truly ballistic impact. A lack of additional force during the impact may have resulted in the relatively flat slope of the linear regression, differences in combat sports athletes would potentially be much greater, providing a more informative regression analysis. As a result, we believe that further research using human participants is needed before rate of force development is accepted or rejected as a valid measure from this method of dynamometry.

Finally, this method of dynamometry is affected by the bag's inertial characteristics. The very characteristic that makes the method more relevant to measuring striking impacts results in a target moving with similar inertia to that of a human or training tool. This limits the device to only measuring a single strike at a time. This is a limitation of all inertially relevant dynamometry and has been identified by Smith et al. (2000) previously. As such, our method is only appropriate for the analysis of maximal striking impacts and not multiple strikes. The relevance of single versus multiple strike measurement has not been explored in relation to combat sports performance. We contend that, for the purpose of analysing and increasing striking impact performance, the multiple strike measurement is not paramount (Girodet et al., 2005; Neto et al., 2012; Walilko et al., 2005). Regardless of the number of strikes performed or actual values of the impact, this method has been found to produce reliable results that are valid in the ability to differentiate kinetic magnitudes from ballistic pendulum impacts. Further study is need with human participants to confirm if this is a reliable method for identifying differences between participants, and within participants over time.

Conclusion

This study developed and tested a novel method of striking dynamometry that is reliable and internally valid in measuring impulse, and peak and mean force in pendulum impacts. This method has minor issues related to the use of a standard commercial striking bag, specifically the need to pre-compress the bag with impacts. Still, the method is relatively simple to use, requiring only a teardrop bag and a triaxial accelerometer and does not necessitate any major adjustments to either piece of equipment to provide the information needed to analyse striking performance. This method can also be simply applied to any other hanging striking bag of similar length. There exists a multitude of devices to measure striking impact kinetics, and while such diversity in the characteristics of the devices exists comparison is problematic. The method we present offers arguably the most practical approach to striking dynamometry developed to date. Further studies are needed to explore the usefulness of the device with human participants and explore the rate of force development measure.

CHAPTER 6

VARIABILITY AND RELIABILITY OF PUNCHING IMPACT KINETICS IN UNTRAINED PARTICIPANTS AND EXPERIENCED BOXERS

Reference

Lenetsky, S., Brughelli, M., Nates, R.J., Cross, M.R., & Lormier, A.V. (2018). Variability and reliability of punching impact kinetics in untrained participants and experienced boxers. *Journal of Strength and Conditioning Research*, 32(7), 1838-1842.

Author contribution

SL: 80%, MB: 5%, RJN: 5%, MRC: 5%, AVL: 5%

Preface

The results of Chapter five established a method to measure impact kinetics, and the validity and reliability of said method. Chapter six serves to confirm the reliability of this method with human participants. The findings of this chapter support the use of this method throughout the remainder of the thesis.

Abstract

Striking impact kinetics are central to performance in combat sports. Despite a multitude of assessment, few in the literature have explored the variability and reliability of punching force assessment. Consequently, this study assessed the variability and reliability of measured punching impact kinetics in untrained and experienced boxers, using a recently developed and validated method of striking dynamometry. Intra-session (both cohorts) and inter-session (untrained only) measures of impulse, peak and mean force were determined across four punch types (jabs, crosses, lead and rear hand hooks) using coefficient of variation (CV), intra-class correlation coefficients (ICC), and typical error of measurement (TEM). Moderate (ICC < 0.67 or CV > 10%) to small (ICC > 0.67 and CV <10%)

variability was found for intra-session results of both groups, the majority having small variability. Inter-session findings of the untrained cohort had a similar spread of variability, but with the majority exhibiting moderate variability. All variables except for mean force of the cross in the experienced boxer cohort were found to exhibit a “moderate” magnitude of reliability determined by standardised TEM scores (TEM = 0.60-1.19) during intra-session testing. All variables had moderate reliability during inter-session. This method was found to have acceptable variability and reliability when monitoring punching impact kinetics.

Introduction

The measurement of striking impact kinetics is of vital importance to performance in full contact combat sport (e.g. boxing) (Lenetsky et al., 2013). Previous authors have identified that striking impact kinetics measured during impact can be used to identify skill level (Neto et al., 2007; Smith et al., 2000), fighting style (Filimonov et al., 1983), and even predict the winner of boxing bouts (Pierce et al., 2006). Given the importance of the assessment of specific abilities to sporting success, numerous devices and methods have been proposed with the aim of accurately measuring variants of striking performance (Lenetsky et al., 2013). However, most studies have established reliability using mechanized striking simulations (pendulums, load cells, etc.) and not with human participants (Busko et al., 2014; Y. Fortin et al., 1995; Lenetsky, Nates, Brughelli, & Schoustra, 2017). This is problematic, as the basis of an assessment’s value to sports science practitioners is its ability to measure worthwhile changes in athletes (Haugen & Buchheit, 2016).

Recently, a simple, affordable, and valid alternative method has been developed to assess striking impact kinetics (Lenetsky, Nates, et al., 2017). While found to be highly reliable when validated with a ballistic pendulum, it is currently unknown whether this new method provides appropriate assessment of combat sports athletes. The natural variability in human movements may not produce reliable results with this method. The purpose of this study was to evaluate the variability and reliability of this method in two cohorts, a group of experienced boxers and a group of untrained participants. Intra-session and inter-session reliability and variability were explored to find the feasibility of this method of striking impact kinetic measurement in combat sports athletes.

Methods

Experimental approach to the problem

Two cohorts of ten participants were assessed performing four types of punches (jab, cross, lead hand and rear hand hooks). One cohort comprised of experienced and competitive boxers, while the other cohort comprised healthy untrained participants. A second data collection was performed one week later with the untrained cohort to assess test re-test reliability.

Subjects

Ten experienced and competitive male boxers (age = 25.6 years ± 5.97, height = 179.5 cm ± 7.72, weight = 95.66 kg ± 21.82, and years training = 10.3 years ± 5.97) and ten healthy untrained participants (age = 30.2 years ± 4.49, height = 176.44 cm ± 6.64, and weight = 75.80 kg ± 4.49) volunteered for this study. 'Experienced' was defined as having three or more years of training in boxing and 'competitive' was defined as having an amateur or professional bout either in three months preceding assessment, or planned in the three months following assessment. The untrained cohort had less than three formal striking based combat sport trainings in their lifetime. All participants were instructed on the data collection protocol and signed acknowledgement of informed consent before testing commenced. All procedures were approved by the Auckland University of Technology Ethics Committee (12/332) for this study.

Equipment

Following the methods of Lenetsky et al. (Lenetsky, Nates, et al., 2017), an inertially modelled teardrop bag (Teardrop style, NZ Boxer, Auckland, New Zealand) was attached with a 3D accelerometer (Model 4630A, Measurement Specialties, Aliso Viejo, CA, United States) to measure punching impact kinetics (Figure 1). The accelerometer data was sampled at 1000 Hz, collected through a VICON system (Version 1.7, VICON Inc., Denver, CO, United States). To ensure accuracy of the punches on the designated target area a high-speed camera (EOS

5D Mark 3, Canon, Japan), sampling at 200 Hz, was used to review each punch after it had been performed. Punches which did not land on the target were discarded until seven successful punches had been recorded. This was required as punches off of the target would alter the calculations used to find impact kinetics (Lenetsky, Nates, et al., 2017). All participants wore the same model boxing gloves (NZ Boxer Boxing Gloves 16oz, NZ Boxer, Auckland, New Zealand) and hand wraps (NZ Boxer 2.5m Hand Wraps, NZ Boxer, Auckland, New Zealand).

Figure 8. A front and side view of a similar tear drop bag equipped with an accelerometer and marked with an impact target.

Data collected from the above equipment was analysed with a custom-made LabVIEW programme (Version 11.0, National Instruments Corp., Austin, TX, USA). The programme used the previous mathematical approach developed for this method (Lenetsky, Nates, et al., 2017), using unfiltered acceleration data and inertial modelling of the striking bag to calculate impulse, mean and peak force. Identification for the time of the impact followed this method's standard procedure, starting at the clear point of impact (visually identified), and ending at the first data point under a 400N threshold as seen in Figure 9. All variables were calculated from the identified time of impact and followed established procedures (Lenetsky, Nates, et al., 2017).

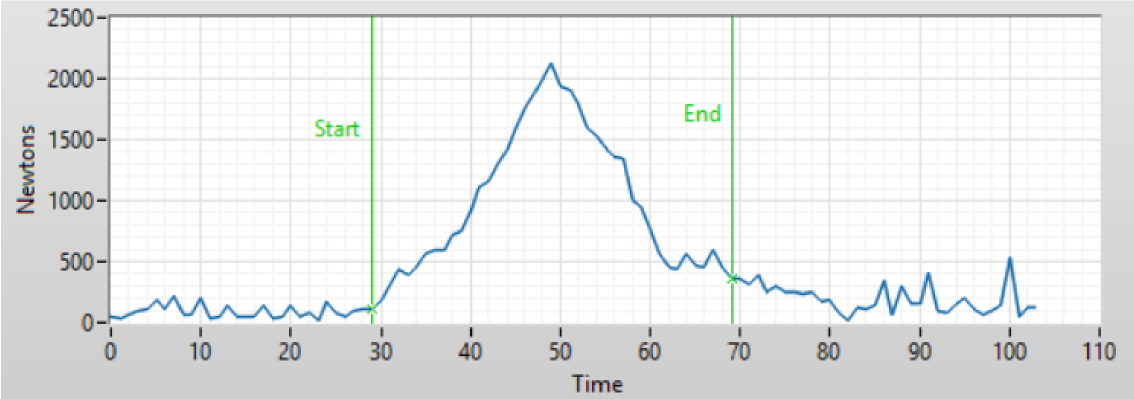


Figure 9. Time of impact readout from the LabVIEW programme.
The "Start" and "End" lines identify the start and end of the section of the force-time curve analysed for each punch.

Procedures

All participants in this study wore hand wraps for protection and standardisation of hand compliance during impact. Experienced boxers were allowed to wrap their own hands as per their usual technique, the untrained group had their hands wrapped by the lead investigator. Following hand wrapping, all participants performed a standardised warm-up consisting of general cardiovascular exercise, dynamic stretches, and a specific shadow boxing warm-up. Following the standardised warm-up, all participants performed a series of practice punches to familiarise themselves with the collection procedure.

Data collection consisted of each participant performing seven maximal punches of each type. A minimum of one minute of rest was provided between each punch. Punches were performed as groups per each punch type (all crosses followed by all jabs, followed by all lead hand hooks, etc.). As per Lenetsky et al. (2017), the bag was tested for the minimum impacts needed until deformation plateaued (an observed levelling off of in the change of mean scores between each trial). Testing determined two impacts were required for this bag, and consequently, the first two punches performed of each type were removed from the analysis. This procedure is in accordance with previous research (Lenetsky, Nates, et al., 2017), to more accurately and reliably reflected the punching impact kinetics of the participants. The contents of the bag were adjusted to their initial state between each punch type to standardise the above process.

Statistical analysis

Mean and standard deviations (SD) were calculated for all impact variables in both groups. All data were log-transformed for analysis to correct for heteroscedastic effects and analysed using an Excel spreadsheet (*xrely.xls*) from sportsci.org (Hopkins, 2000). Intra-session statistical analysis was performed on variables for all five trials. Inter-session analysis was performed on the mean results of the variables for each individual session. Intraclass correlation coefficients (ICC) and coefficient of variation (CV) were used to explore relative and absolute variability. 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% (Bradshaw, Hume, Calton, & Aisbett, 2010). Reliability was examined with standardised typical error of measurement (TEM), and to provide the reader with a practical interpretation of magnitude of error expected for any change in the mean. Magnitudes of reliability effects were calculated by doubling the TEM result (Smith & Hopkins, 2011). Thresholds of 0.2, 0.6, 1.2, 2.0, and 4.0, were used for small, moderate, large, very large, and extremely large magnitudes respectively (Hopkins et al., 2009).

Results

Mean and SD results of both cohorts is found in Table 8 for all punches. Intra-session variability and reliability are found in Table 9. All intra-session results were found to have moderate to small variability for all punches in both groups (Bradshaw et al., 2010). Test re-test variability and reliability results of the untrained cohort are located in Table 10. Small to moderate variability was found in the test re-test data for all punches. TEM magnitudes where moderate to large in intra-session testing for both cohorts and moderate in test re-test results of the untrained cohort.

Table 8. Session 1 mean and standard deviation.

	Jab	Cross	Lead Hand Hook	Rear Hand Hook
Trained				
Peak Force (N)	2547 ± 776	4695 ± 673	4058 ± 109	4749 ± 107
Mean Force (N)	1279 ± 323	1998 ± 177	1708 ± 361	1971 ± 274
Impulse (N·s)	49 ± 12	75 ± 8	59 ± 12	68 ± 14
Untrained				
Peak Force (N)	1411 ± 365	2395 ± 966	2316 ± 787	2427 ± 940
Mean Force (N)	860 ± 217	1178 ± 386	1158 ± 325	1220 ± 350
Impulse (N·s)	26 ± 7	42 ± 16	37 ± 14	38 ± 15

Table 9. Intra-session variability and reliability.

		Jab	Cross	Lead Hand Hook	Rear Hand Hook
Trained					
Peak Force	CV (%)	12.0	9.3	6.6	7.7
	ICC	0.89	0.73	0.96	0.93
	TEM	0.37	0.57	0.23	0.29
Mean Force	CV (%)	9.8	5.8	10.3	7.0
	ICC	0.89	0.59	0.84	0.83
	TEM	0.38	0.68	0.46	0.46
Impulse	CV (%)	7.1	4.4	7.7	6.4
	ICC	0.94	0.86	0.91	0.95
	TEM	0.29	0.42	0.34	0.27
Untrained					
Peak Force	CV (%)	13.3	10.0	9.3	9.4
	ICC	0.81	0.97	0.95	0.96
	TEM	0.48	0.21	0.25	0.24
Mean Force	CV (%)	9.9	8.3	5.5	7.8
	ICC	0.89	0.96	0.97	0.95
	TEM	0.38	0.23	0.18	0.26
Impulse	CV (%)	10.3	7.8	5.7	10.5
	ICC	0.90	0.98	0.98	0.94
	TEM	0.37	0.18	0.15	0.28

Table 10. Test re-test variability and reliability of the untrained cohort.

		Jab	Cross	Lead Hand Hook	Rear Hand hook
Peak Force	CV (%)	14.6	18.8	7.7	11.9
	ICC	0.79	0.89	0.96	0.93
	TEM	0.50	0.38	0.22	0.30
Mean Force	CV (%)	14.6	13.8	7.4	10.4
	ICC	0.71	0.90	0.96	0.91
	TEM	0.58	0.37	0.24	0.34
Impulse	CV (%)	14.3	15.6	12.1	10.5
	ICC	0.82	0.91	0.91	0.94
	TEM	0.47	0.34	0.35	0.28

Discussion

The punching results calculated with this method presented small to moderate variability and moderate to large errors in reliability. To the authors knowledge, this is the only publication on a method of assessing punching kinetics to have such a thorough analysis of data and use a multi-cohort sample (trained and untrained).

The trained cohort had lower CV scores than the untrained on all measures apart from mean force of the lead hand hook. This is to be expected as an increase in the variability of performance measures has been found in those with less/no training in specific movements (Smith & Hopkins, 2011). Considering the inherent high variability of the untrained group performing this complex task, the moderate variability found in the majority of test re-test results (ten of twelve) is not surprising. Only the lead hand hook had measures with small variability (peak and mean force). While this level of variability is clearly not ideal for practitioners wanting to monitor changes in these variables, we should expect that well-trained athletes would exhibit lower error across well practiced striking movements given similar trends (decreased error with increased familiarity) have been found observed in other simple explosive movements (Claudino, Mezencio, Soncin, & Serrao, 2013). Additionally, taking a mean of the five (or potentially more) trials performed in a session (Claudino, Cronin, Amadio, & Serrao, 2016), differing instruction to the participants, and potentially expanding the target area (if feasible) may all serve to improve the variability and reliability of this method.

Regardless of any effects familiarisation may have on variability and reliability, the findings from this study show that this method demonstrations promise for the accurate assessment of striking kinetics, when limitations due to subject familiarity are considered. This analysis was possible using a simple and affordable method, that used a target relevant to the sport, a rarity in the literature. Consequently, we believe the method provides value to those operating in both research and field testing, when applied with consideration. Further research is needed to: 1) explore test re-test variability and reliability in trained participants when punching; 2) develop protocols to reduce variability and typical error in the measures; 3) examine the reliability and variability of this method with other types of strikes (kicks, knees, elbows, etc.); and 4) explore statistical approaches such as minimal individual difference (Claudino, Cronin, Oinho, et al., 2016).

Conclusion

Using Lenetsky et al.'s (2017) method of striking dynamometry to assess punching impact kinetics, exhibits small to moderate variability, and moderate to large errors in reliability when assessing untrained and trained participants. This indicates that the method used for assessment has acceptable variability and reliability when consideration (comparison of TEM to specific cohort's smallest worthwhile change) is used to monitor punching impact kinetics. Further examination (collection protocols and test re-test studies on experienced boxers) would serve to further improve the method in the future.

Section 3:

Biomechanical assessment of punching kinetics

CHAPTER 7

DEFINING THE PHASES OF BOXING PUNCHES: A MIXED METHOD APPROACH

Reference

Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Defining the phases of boxing punches: A mixed method approach. *Journal of Strength and Conditioning Research*, In press.

Author contribution

SL: 80%, MB: 5%, RJN: 5%, JGN: 5% MRC: 2.5%, AVL: 2.5%

Preface

With a theoretical basis and the practical method needed to measure impact kinetics established in the thesis, Chapter seven directly addresses the biomechanics of punching in boxing. The chapter uses a mixed method approach to produce the first evidence supported description of the kinematics, GRF kinetics, and muscle activation patterns of punching; the latter two variables identified in Section 1 as potential keys to punching impact kinetics. This chapter focuses on qualitative descriptions of straight and hook punches and the definition of the phases of punching. This focus provides Chapters 8a and 8b with a framework to establish determinants of punching impact kinetics.

Abstract

Current research into punching in boxing has explored both kinematic and kinetic variables, however there is no shared structure in the literature to describe these findings. A common method used to provide a shared structure in other sporting tasks is the definition of movement phases. To define the phases of four punches used in boxing (lead and rear straight and hook punches), ten experienced and competitive boxers (age = 25.6 years ± 5.97, height = 179.5 cm ± 7.72, weight = 95.66 kg ± 21.82, and years training = 10.3 years ± 5.97) were tested while performing maximal effort punches. Ground reaction forces, electromyography, high speed video and striking dynamometry data were collected during all punches. A mixed method approach was employed to define the phases for each punch type based on the ground reaction force measurements and impact timing from the striking dynamometer. Electromyography and high-speed video data were then used to develop a more holistic understanding of punching actions by elaborating on the description of each phase. The final outcome of this approach has produced a structure for current and future punching related research and a context to improve coach/sport scientist communication.

Introduction

There are a multitude of striking based combat sports practiced throughout the world, both culturally and competitively (Garcia & Malcolm, 2010). Boxing is unique among competitive combat sports in that athletes are limited to using only punches to attack opponents (Walsh, 1951). The popularity of boxing, in association with punching being a central tenet of performance in other striking codes, has resulted in researchers striving to quantify the determinants of success in punching performance (Lenetsky et al., 2013). While literature has examined kinetics (Atha et al., 1985; Busko & Szulc, 2014; J. Mack et al., 2010; Walilko et al., 2005), kinematics (Cabral et al., 2010; Cheraghi et al., 2014; Whiting et al., 1988), and training response on measures of performance (Stanley, 2014), no clear shared structure of phases to define punching actions exists.

In biomechanical research describing sporting actions, the practice of braking a movement into phases delimited by key events provides structure on which to standardise the movement analysis (Bartlett, 2007). These phases allow for ease in both quantitative and qualitative analysis and have been used to explore kinematics (Angulo-Kinzler et al., 1994; Bretigny, Seifert, Leroy, & Chollet, 2008) and kinetics (Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999) in a variety of movements, both cyclical (Smith, McNitt-Gray, & Nelson, 1988) and acyclical

(Pori, Bon, & Sibila, 2005). Punching in boxing is interesting in that it can be performed both cyclically and acyclically depending on the demands of the situation (Dempsey, 1950). Regardless of the punch or punches used in competition, the fundamentals are consistent (Slack, 2012), and thus the definition of objective phases is appropriate when analysing single punches.

Commonly in sport, the definition of phases is performed using kinematic findings and qualitative factors (Lees, 2002), kinetic data has also been used to establish phases of movements (Yu, Broker, & Silvester, 2002). In boxing, there has recently been a focus on the lower body's role in punching performance (Lenetsky et al., 2013; Loturco et al., 2014; Loturco et al., 2015; Stanley, 2014). This topic has been explored through quantitative methods focused on kinetics (Loturco et al., 2015), and qualitative interviews of experienced boxing coaches (Lenetsky & Lindsay, 2017). The findings of these studies indicate that the lower body's contribution to punching is vital for performance. Experienced boxing coaches explicitly stated that "foot work" was the dominant component of effective punching. Kinetic findings from the lower body should therefore be included in identifying the phases for punching.

Muscle activation patterns have also been identified as an important factor in punching performance. Specifically, the use of double peak muscular activation (DPMA) has been theorized to enhance effective mass (Lenetsky et al., 2015) and improve punching velocity (McGill et al., 2010). There has been no exploration of the role of DPMA in relation to the lower body's contribution to punching. Additionally, there is a paucity of research exploring the temporal component of DPMA, which could be seen in the context definition of phases.

Data collection consisted of the capture of ground reaction forces (GRF), electromyography (EMG), and 2D high-speed video (HSV), collected from a cohort of experienced boxers performing isolated, single punches. Quantitative and qualitative analysis of the GRF data was then used to identify the phases of selected punches. This construct was then expanded with EMG and HSV data to produce a holistic understanding of punching actions.

Methods

Experimental approach to the problem

A cohort of trained boxers performed a selection of straight and hook punches (straight punches = jab [lead hand] and cross [rear hand]; hooks = lead hand hook and rear hand hooks) common in boxing. During the execution of these punches GRF data, EMG results, and HSV footage were used to elaborate the phases of punching. This definition of phases followed a mixed methods paradigm, using quantitative data and qualitative methods.

Subject

Ten experienced (greater than 3 years' experience) and competitive (having a bout three months preceding assessment, or planned in the three months following assessment) male boxers volunteered to participate in this study (age = 25.6 years ± 5.97, height = 179.5 cm ± 7.72, mass = 95.66 kg ± 21.82, and years training = 10.3 years ± 5.97). All participants indicated they were free of injuries that would affect their ability to punch maximally. All participants were informed of the collection protocol and signed consent before their testing. The methodological procedures of this study were approved by the Auckland University of Technology Ethics Committee (12/332).

Collection protocol

All participants were prepared for electrode placement bilaterally on the triceps brachii (LTB and RTB), latissimus dorsi (LLD and RLD), rectus abdominis (LRA and RRA) and rectus femoris (LRF and RRF). Preparation and placement of electrodes followed the protocols of Konrad (Konrad, 2006). Electrodes with resistance higher than 10 Koh were reapplied following the above procedure. The participants performed a standardised warm-up consisting of five minutes of moderate intensity cardiovascular exercise (no more than 5 out of 10 perceived effort on a modified Borg scale (Borg, 1982)) and dynamic stretches. Following the warm-up, maximal voluntary isometric contractions (MVIC) were performed for all relevant muscle groups according to standardised procedure (Konrad, 2006).

Following MVIC testing, all participants performed a specific warm-up consisting of shadow boxing and practice punches of each type (straight and hook). Data collection consisted of seven repetitions of each punch type performed against a standard striking bag (NZ Boxer, Teardrop style, Auckland). Each punch was executed maximally with one minute of rest prescribed between each effort. The boxers were allowed to self-select their distance from the striking bag, and the specifics of the technique (within the realms of the punching discipline prescribed), in an effort to promote maximal performance (Halperin et al., 2016).

Equipment

For each punch GRF data were collected via two force plates (Accupower, Advanced Mechanical Technology, Inc., Wattertown, MA, United States) and sampled at 1000 Hz. Each plate was positioned, one under each leg, and was arranged to allow for individualised foot positioning. An eight channel EMG system (AMT-8 "Octopus", Bortec Biomedical Ltd., Calgary, Canada) collected muscle activation data (1000 Hz sampling rate). A HSV camera (A602fc-2, Basler, Germany) was used to collect visual data (200 Hz sampling rate). The HSV was positioned to record the sagittal plane of the athletes and was aligned to the striking bag to minimise parallax error. Impact timing was measured with Lenetsky et al.'s (Lenetsky, Nates, Brughelli, & Schoustra, 2016) method of striking dynamometry using a tri-axial accelerometer (Model 4630A, Measurement Specialties, Aliso Viejo, CA, United States) sampling at 1000 Hz. This method of striking dynamometry allowed for the identification of the moment of impact (Lenetsky, Nates, et al., 2017). All data from the force plates, EMG system, HSV camera, and striking dynamometer were time synchronized using a VICON system (Version 1.7, VICON Inc., Denver, CO, United States).

Analysis

Force plate data were smoothed with a 100 Hz low pass Butterworth filter and analysed using a custom MATLAB programme (R2016a, MathWorks, Natick, MA, United States). EMG data processed using a custom MATLAB programme, and filtered according to the guidelines of the International Society of Electrophysiology and Kinesiology, and literature exploring punching EMG (McGill et al., 2010; Merletti & Di Torino, 1999). A band pass Butterworth filter (10 - 450 Hz, full wave rectified) was applied before a low pass (3 Hz) filter was used to produce a linear envelope. The linear envelope was normalised to the MVIC data. All EMG data were verified, and erroneous data were removed from analysis. The remaining data were analysed for mean and standard deviation results. Temporal punch impact data was calculated using a custom LabVIEW programme (Version 11.0, National Instruments Corp., Austin, TX, USA) to identify the beginning and ending of the impact period of each punch. All GRF and EMG data were temporally normalised around impact data for cross comparison of each punch. Qualitative visual analysis of HSV was performed using a Kinovea software package (Version 0.8.15).

To define the phases, GRF data from all punches were averaged and standard deviations calculated across the entirety of the signal for analysis. Qualitative decisions based on the quantitative data were made by the authors to identify the phases of the four punch types. This process was performed through qualitative triangulation of the primary author, an expert in combat sports striking (Coté et al., 1995), and an experienced biomechanist (Marshall & Rossman, 2014).

The analysis of the phases in the study does not address a preparation or recovery phases of the punches examined. This is due to a limitation of our data collection and a fundamental constraint of boxing. In a live boxing match, punches can be thrown in combination with other punch types or with defensive actions (Slack, 2012). We do not believe the lack of a preparation or recovery phases impact our results greatly. The constant variation found in live boxing matches will not allow for a consistent preparation or recovery phase, but the fundamentals of the punches once begun, should remain consistent to our findings. We see this in part in our own findings, as differences in phase length between the boxers tested add variance to our overall results, yet the fundamental pattern remains the same across our cohort. Without a preparation or recovery phase, the phases identified are: initiation, execution, and impact. Specific to hook punches, a fourth phase, wind-up, was included before the initiation phase.

Results

GRF results

Mean and standard deviations for the average of the cohorts 7 punches are presented in Figures 10 – 13. Phases are indicted in Figures 10 through 13 for the jab, cross, lead hand hook (LHH), and rear hand hook (RHH) respectively. In these figures, the positive Y direction is longitudinally towards the bag, the positive Z direction is vertical loading and the positive X direction is laterally to the lead leg of the boxer. The phases of punching were defined as follows:

Jab (see Figure 10)

<u>Phase 1 (Initiation)</u>

The initiation phase began with a 10% increase in GRF in the Z-axis of the rear foot from baseline, indicating loading before the punch is thrown. Throughout the initiation phase, the boxers continued to load the leg vertically before propelling themselves forward (Y-axis) toward the target with the rear leg. During the forward movement, the boxers unloaded (a decrease in GRF) their front leg in the Z-axis leading to a step or slide forward. The ending of the initiation phase was marked by a peak vertical force produced by the rear leg. No pertinent findings were found for the X-axis in this phase.

<u>Phase 2 *(Execution)*</u>

As the rear leg reached peak loading in the Z-axis (i.e. starting point of the execution phase) there was continued forward drive produced in the Y-axis. As the execution phase continued the lead leg made contact with the ground, accepting bodyweight. This lead leg loading occurred moments before impact with the target. Impact marks the end of this phase.

<u>Phase 3 (Impact)</u>

During impact, the lead leg experienced continued loading in the Z-axis. Simultaneously, the lead leg applied forces away (posteriorly) from the target (Y-axis) and rear leg unloaded almost completely.

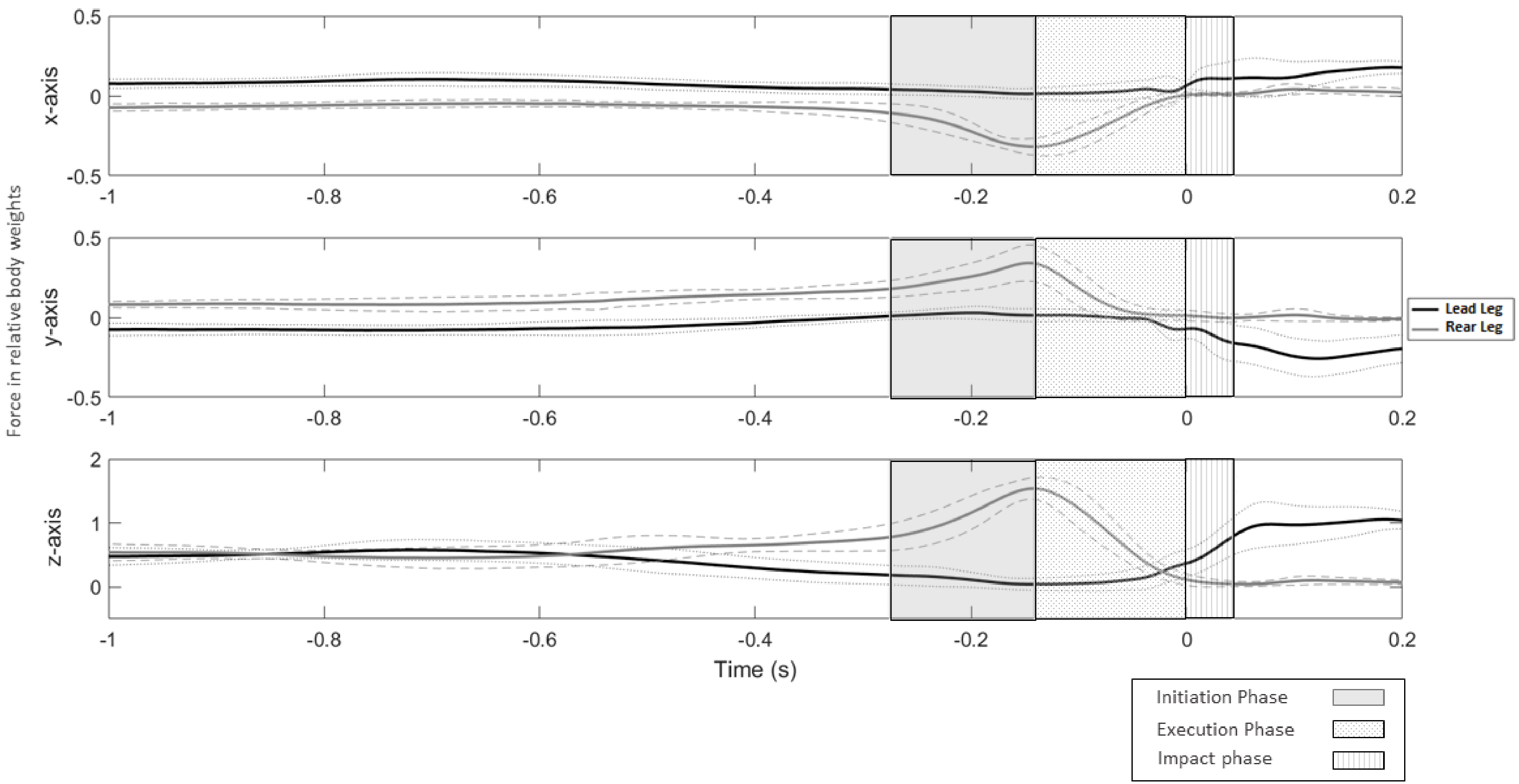


Figure 10. Combined mean and standard deviation of individual jab GRF means with phases.

Cross (see Figure 11)

Phase 1 (Initiation)

The initiation phase of the cross started as the boxer pushed away from the target with the lead leg (ten percent decrease in GRF of the Y-axis from baseline). As the boxer pushed away from the target with the lead leg, the rear leg drove forward into the target. Concurrently, vertical loading shifted from the rear leg to the lead. The initiation phase ends as the lead leg reaches peak Y-axis forces applied away from the target.

Phase 2 (Execution)

This phase begins as the boxers' lead leg reaches peak force applied away from the target and continues as they transfer their bodyweight forward, unloading the rear leg. With their weight now on the front leg the boxers reduced the force applied away from the target until impact, marking the end of this phase.

Phase 3 (Impact)

During impact, the boxers continued to apply forward force in the Y-axis with the lead leg. While the lead leg drove forward, there was also force applied away from the mid-line in the X-axis and the Z-axis experienced some unloading. Like the jab, the rear leg remained relatively unloaded throughout the phase.

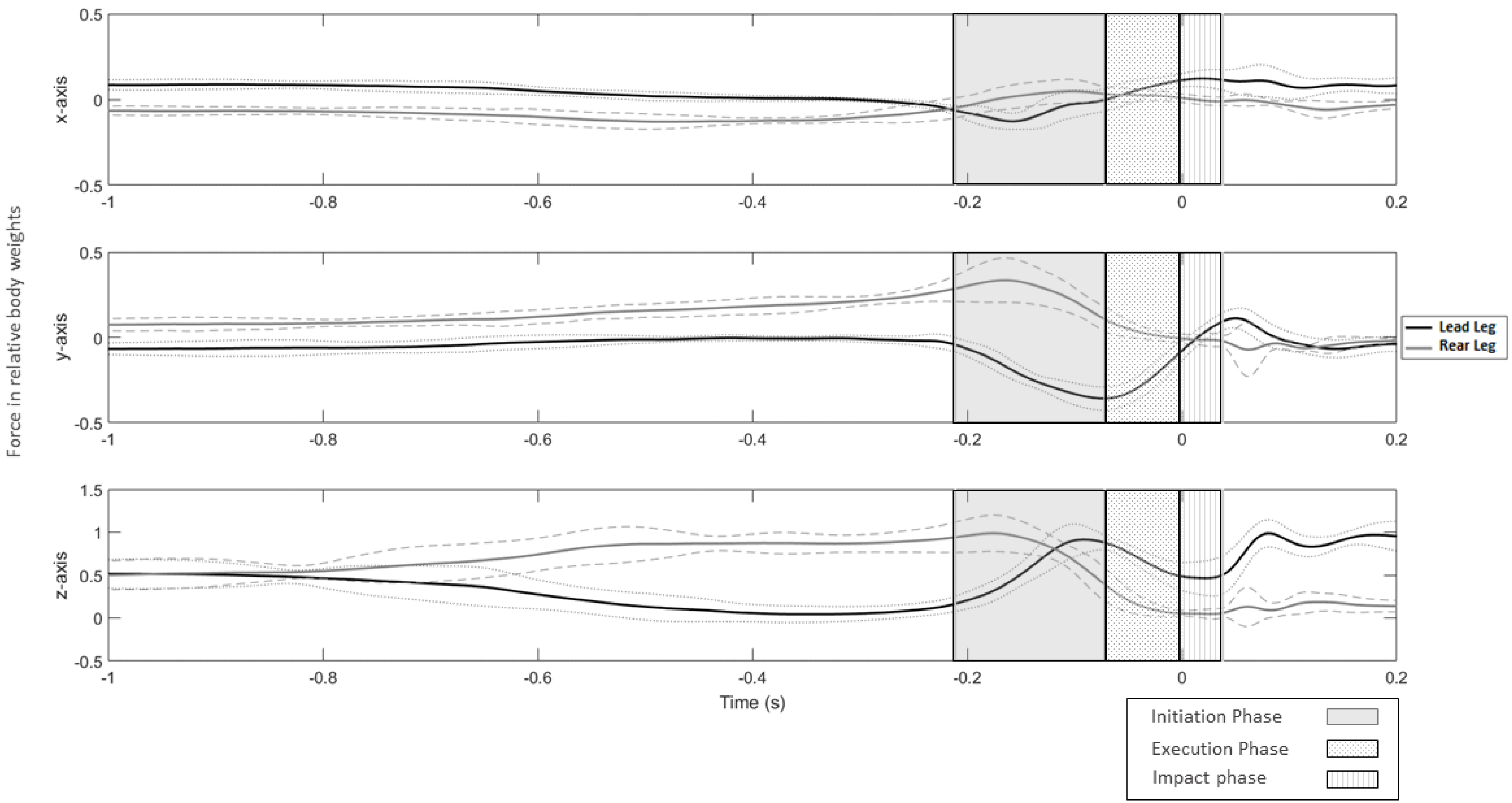


Figure 11. Combined mean and standard deviation of individual cross GRF means with phases.

Lead Hand Hook (see Figure 12)

Phase 1 (Wind-Up)

The wind-up phase started as the boxers shifted their weight from the rear leg to the lead leg (a crossover of signals in the z-axis). As the lead leg accepts weight there was also a slight drive forward, and a drive away from the target with the rear leg (Y-axis). In the X-axis, there was a slight shift towards the mid-line on the lead leg.

Phase 2 (Initiation)

As the lead leg continued to drive forward, the rear leg drove away, and there is a crossover in the Y-axis signal. This crossover marks the beginning of the initiation phase. This pattern of opposing force application in the Y-axis continued through the phase, and similar contrasting force application was found in the X-axis.

Phase 3 (Execution)

The lead leg reaching peak X-axis force away from the mid-line (propelling the body the opposite direction) marks the start of the execution phase. Post X-axis peak, there is a reduction in forward drive (Y-axis) and as impact nears, there was a bilateral drop in vertical loading.

Phase 4 (Impact)

The boxers produce forward drive (Y-axis) off the rear leg during impact, while maintaining relatively little loading in the Z-axis and the X-axis bilaterally.

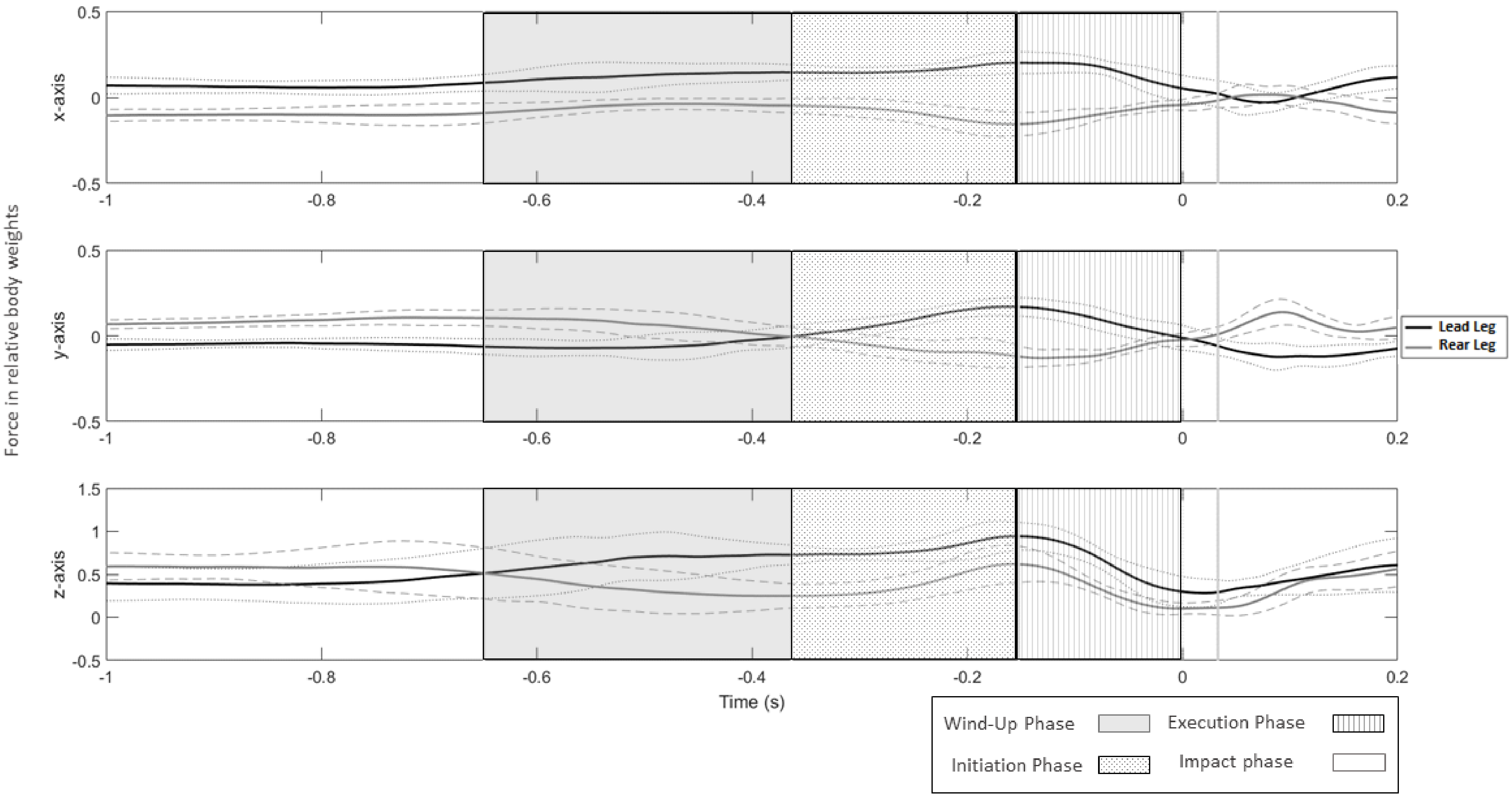


Figure 12. Combined mean and standard deviation of individual LHH GRF means with phases.

Rear Hand Hook (see Figure 13)

Phase 1 (Wind-Up)

Similarly to the LHH, the wind-up phase of the RHH starts as loading in the Z-axis swaps between legs, shifting from the lead leg to the rear, the reverse of the shift that occurred in the LHH. Unlike the LHH, the drive forward produced by the rear leg is not met with an opposite force from the lead leg until the end of the phase.

Phase 2 (Initiation)

The initiation phase begins as the lead leg applies force away from the target (a drop of ten percent in the Y-axis). During this phase, there was a continued drive towards the target from the rear leg in contrast to the forces produced by the lead leg. Correspondingly, a transfer of load occurred from the rear leg to the front leg vertically.

Phase 3 (Execution)

As the lead leg reaches peak force applied away from the target (minimum value in the Y-axis) the execution phase begins. This phase is characterised by a bilateral deloading in the Z-axis, and a reduction of the lead leg GRF applied away from the target. Simultaneously with the drop in Y-axis GRF produced by the lead leg, there was an increase in X-axis force applied away from the mid-line.

Phase 4 (Impact)

The impact phase consisted primarily of a deloaded rear leg vertically, a lead leg drive into the target, and continued force in the X-axis away from the boxers' mid-line.

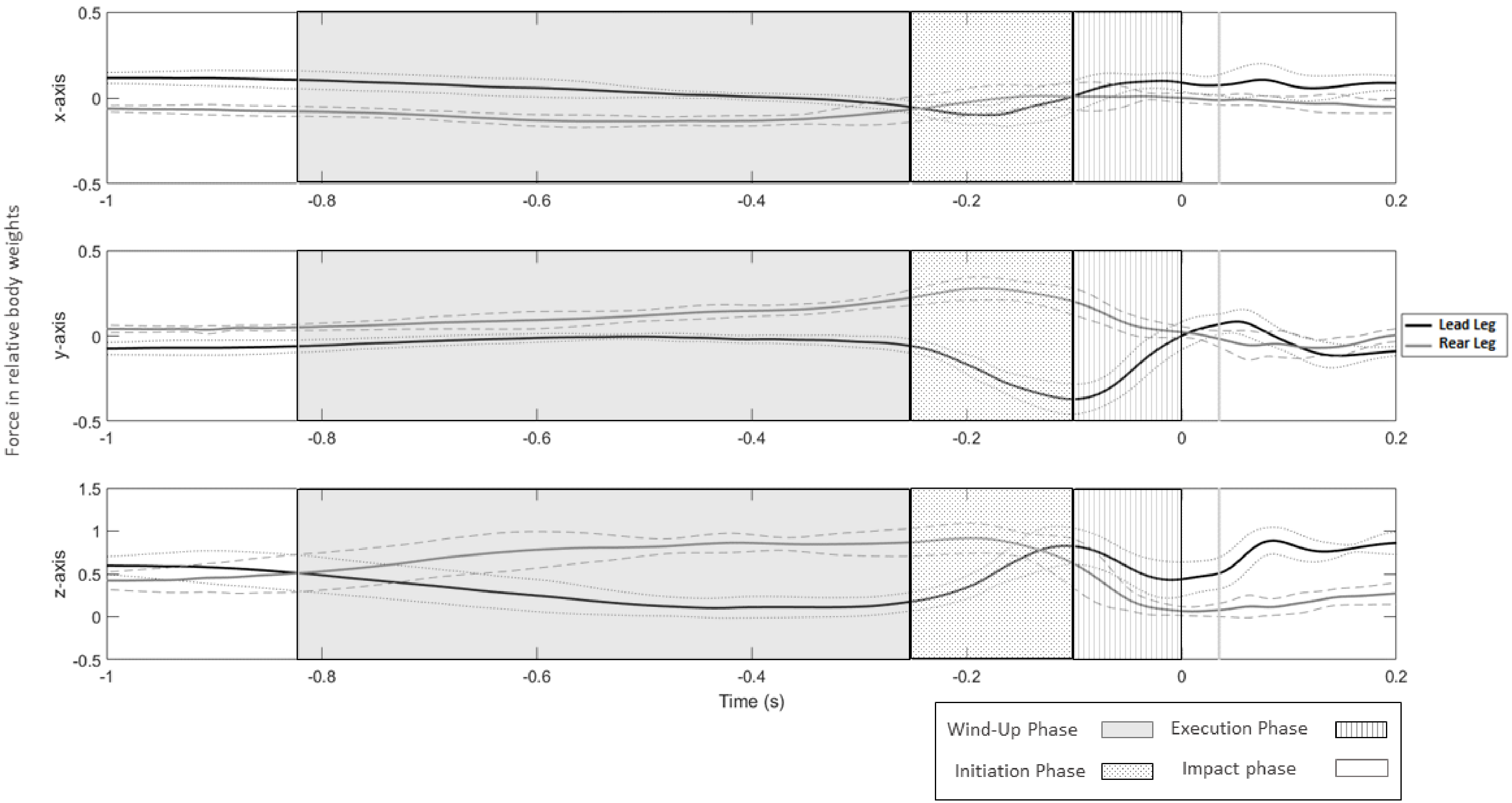


Figure 13. Combined mean and standard deviation of individual RHH GRF means with phases.

EMG results

The EMG results are explained in descriptive qualitative terms, using the phases created from the GRF analysis in Tables 11 – 14. Figures 14 through 17 display the cohort's mean and standard deviation of the means of each individual's seven trials. Phases are indicted in Figures 14 – 17 for the jab, cross, LHH, and RHH respectively.

Jab

Table 11. Qualitative descriptions of EMG activity during the jab.

Phase	Description
Initiation	Increases in muscular activity across all muscles, with RRF being the only muscle to attain peak activity. RRA and LRA near their respective at the end of the phase.
Execution	Early peak activation by RRA and LRA followed by decreases before impact. LRF produces a moderate rise in the middle of the phase while RLD peaks soon after. LLD and LTB peak moments before impact.
Impact	All muscle groups decrease in activation during this phase.

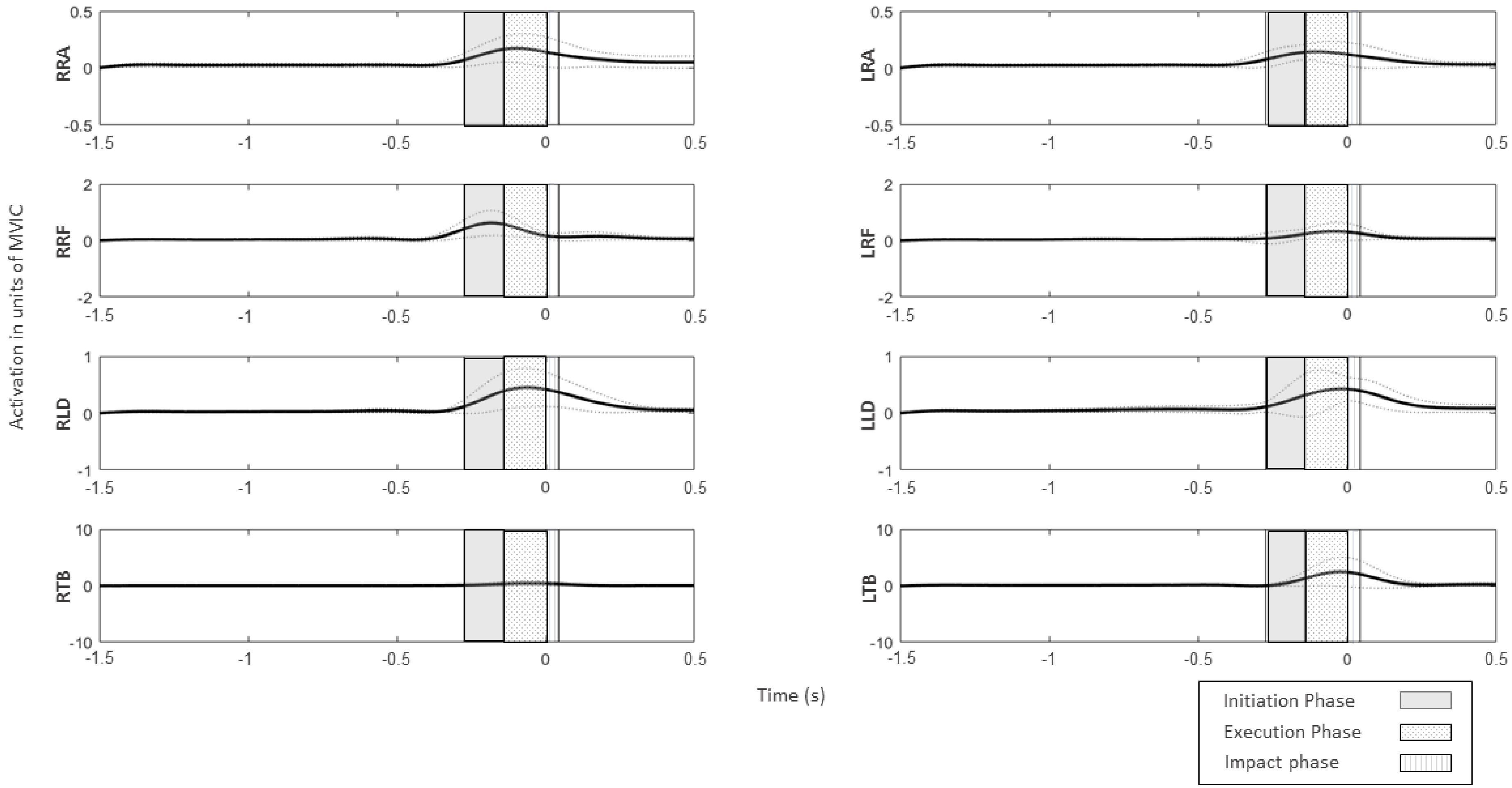


Figure 14. Combined mean and standard deviation of individual jab EMG means with phases.

Cross

Table 12. Qualitative descriptions of EMG activity during the cross.

Phase	Description
Initiation	LRF reaches peak activation immediately after the phase begins, followed by a maximum in the LLD, then RRF, and finally RRA and LRA. There was a large rise in activation of LTB before the initiation phase, followed by a plateau at the beginning of the phase and a continued increase as the phase continued.
Execution	Early in the phase, there is a reduction in activity from peaks in RRA, LRA, and RRF. In the non-punching arm LTB reaches max activation as impact begins.
Impact	All muscles that reached maximal activation before impact continued to see drops in activation. RTB and RLD both reached peak activation at the end of impact.

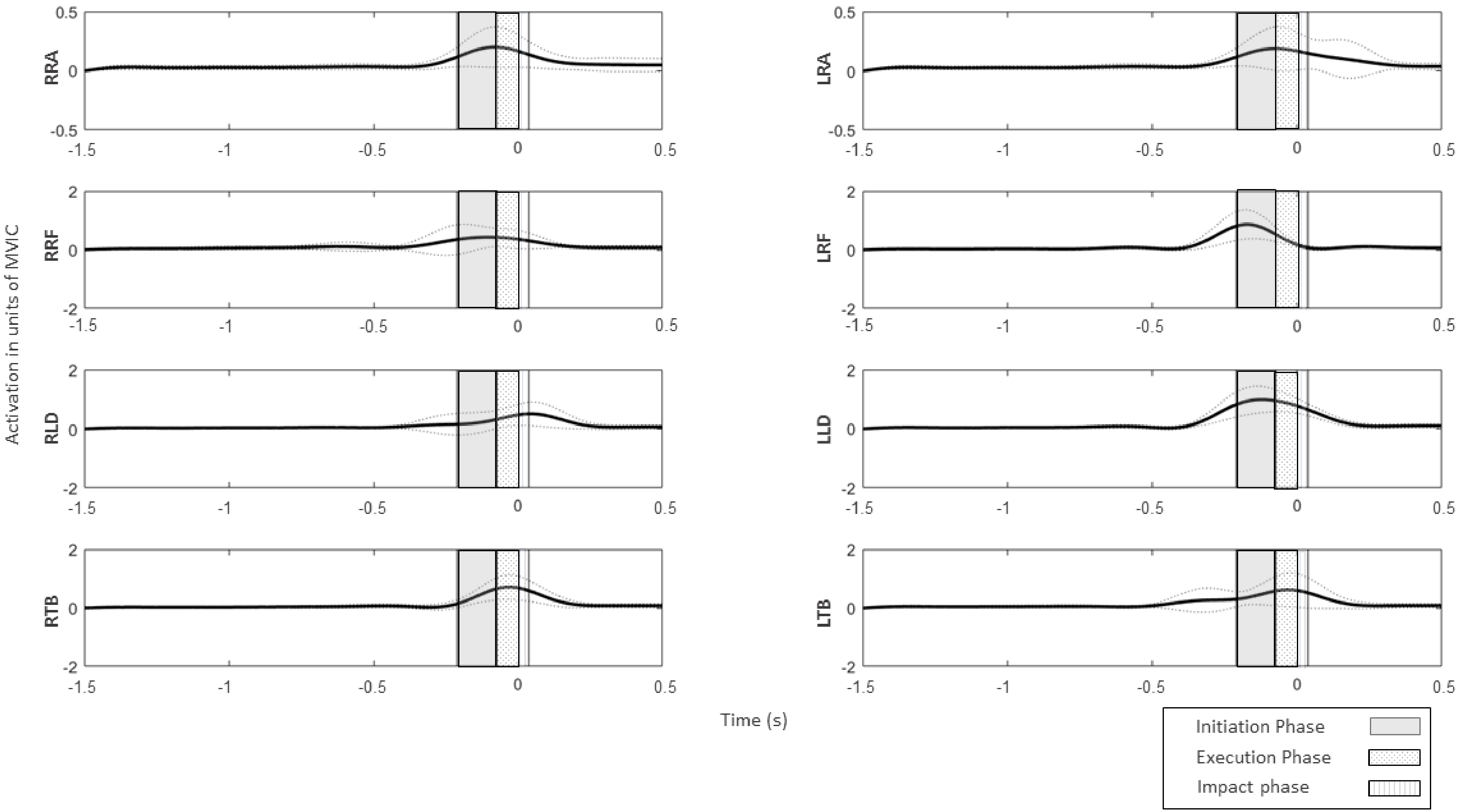


Figure 15. Combined mean and standard deviation of individual cross EMG means with phases.

LHH

Table 13. Qualitative descriptions of EMG activity during the LHH.

Phase	Description
Wind-Up	The majority of muscles had minor activation during this phase, ramping up to their maximal activation in later phases. LTB experienced a drop in activity before it rose again. LLD has the greatest activation, peaking, then dropping, and peaking again as the phase ended.
Initiation	The initiation phase began with a peak of the LLD and LTB which again decreased at the end of the phase. The RLD reached its peak activation soon after the peak of LLD. RRF reached peak near the end of the phase.
Execution	Peaks in both LRA and RRA occur in the early parts of this phase, followed by a relatively minor peak of the RTB. LRF reached peak activation moments before impact. RLD plateaus slightly at impact before a continued drop in activation.
Impact	At the end of the impact phase LLD and LTB reach their third and second peaks respectively.

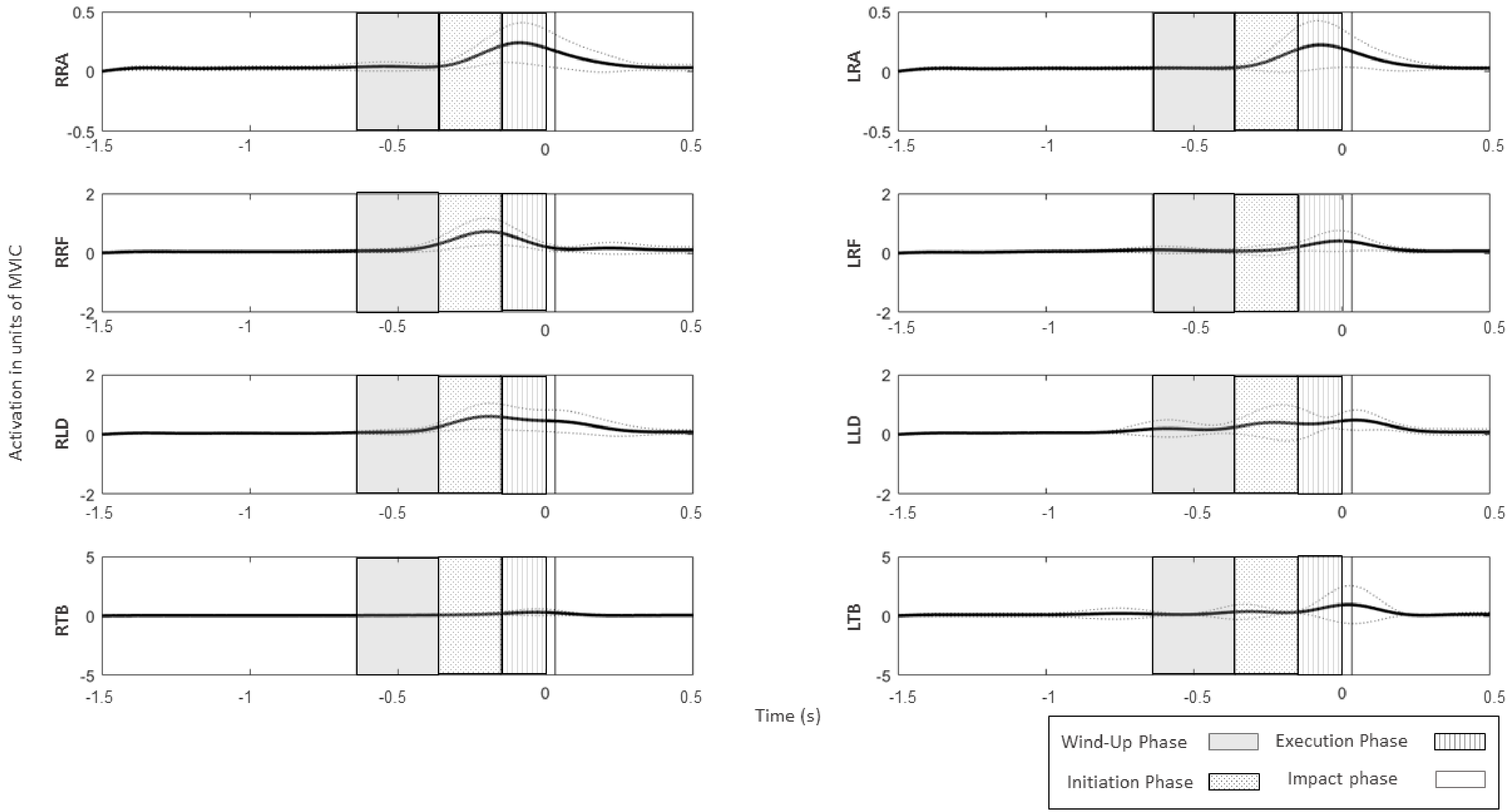


Figure 16. Combined mean and standard deviation of individual LHH EMG means with phases.

RHH

Table 14. Qualitative descriptions of EMG activity during the RHH.

Phase	Description
Wind-Up	Unlike the LHH, small increases were found during the wind-up phase of the RHH. The RRF, followed by the RLD, both increased in activity before drops occurred. All other muscles begin activation in this phase, the LLD greatest of all.
Initiation	The LLD and LRF reached their maximum activation soon after the start of this phase. RRF does not reach a discernible peak, but clearly a plateau began in this phase. RLD reached minimum activation after the high activation found in the wind-up phase, then rebounded as the phase ended. Similarly, RTB had a drop, then rose in activation near the end of the phase.
Execution	The phase began with a peak by the RRA. LRA and LTB followed with peaks at the moment of impact.
Impact	The end of the impact phase is marked by maximal activation in RTB and RLD as contact ends.

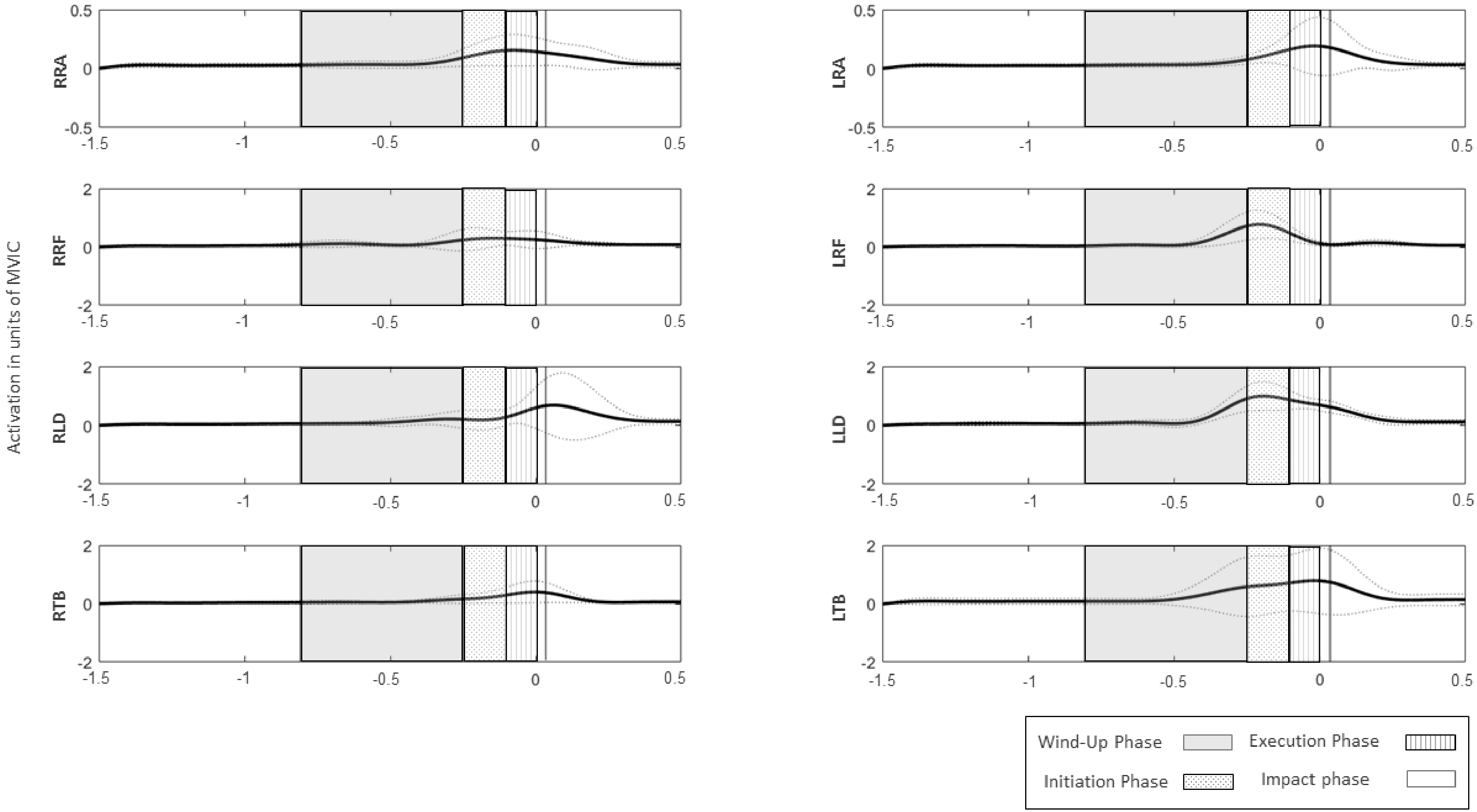


Figure 17. Combined mean and standard deviation of individual RHH EMG means with phases.

Visual analysis results

This descriptive section below was performed using qualitative analysis of HSV. All results are reported in the context of the phases of punching in Table 15 and 16. The impact phase has been excluded from analysis as visually there was little to report. Figure 18 shows a complete view of the visual analysis within the context of the GRF and EMG data of a single participants cross punch.

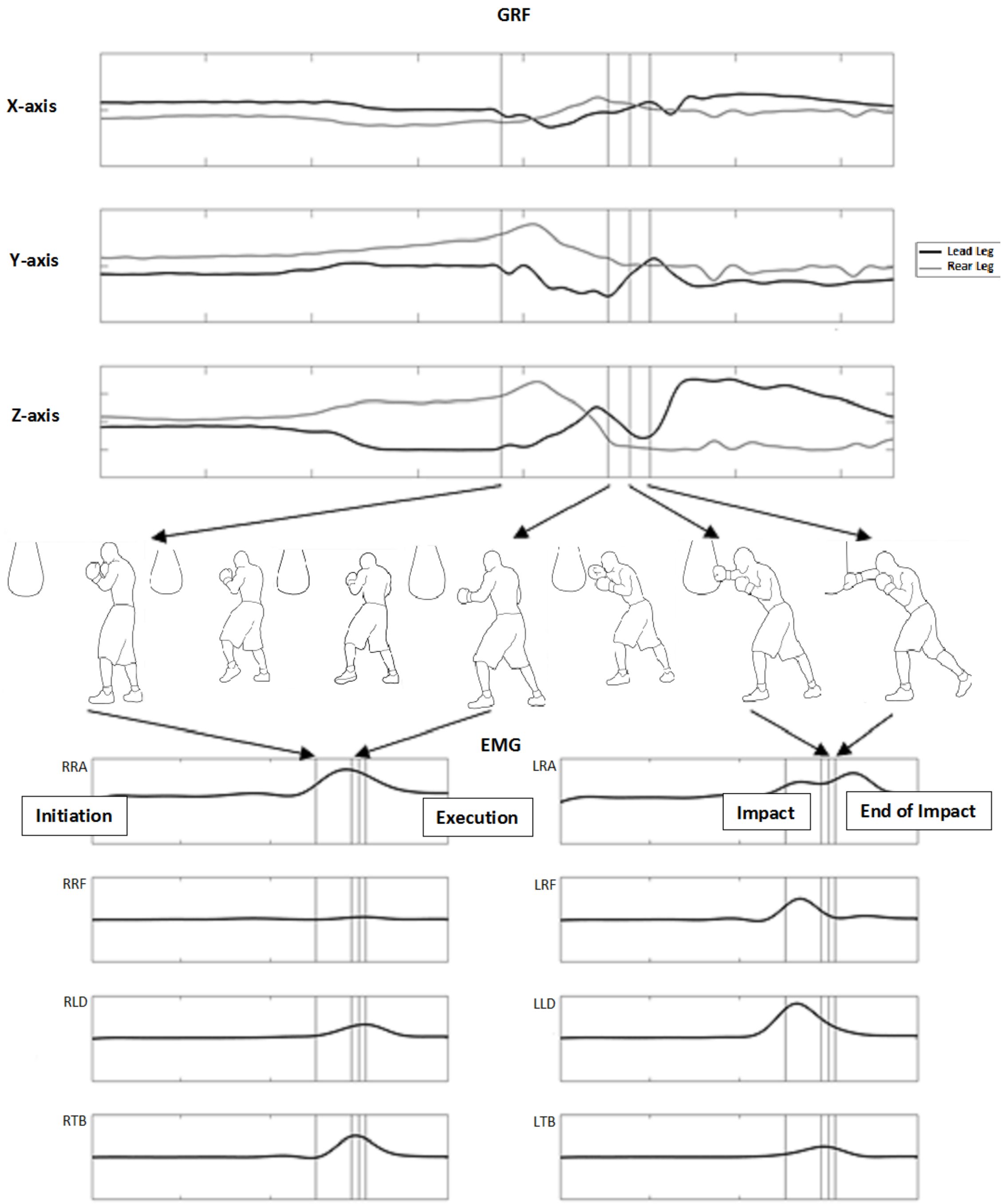


Figure 18. GRF, visual, and EMG results of a single participant's cross punch.

Table 15. Visual descriptions of the straight punches, the jab and cross.

Phase	Description
	Jab
Initiation	The phase starts with a forward step or slide of the lead foot towards the target, combined with an anterior movement of the rear hand. The rear hand does not drop inferiorly towards the waist line, instead, it is maintained in a defensively viable position near the face to protect against incoming punches. Interestingly, there was little torso rotation found throughout this phase.
Execution	The forward step concluded as this phase begins and the rear hand returned to the guard position. Simultaneously, with the return of the rear hand, the attacking arm flexed at the elbow, while rotation of the torso began (attacking shoulder moving towards the target). As rotation continued, the lead arm extended bringing the fist into contact with the target.
	Cross
Initiation	The majority of boxers (7 out of 10) began this phase by first reaching their lead hand out to the target, before pulling it back to the guard position. As the lead hand was drawn back, rotation at the torso and hip began. The attacking arm flexed at the elbow and extends at the shoulder while the rotation occurred.
Execution	As rotation continued the rear foot either rotated internally or a step forward was taken depending on the technique of the boxer. Extension at the elbow and flexion at the shoulder occurred in the attacking arm near the end of the phase before impact.

Table 16. Visual descriptions of the hook punches, the LHH and RHH.

	LHH
Wind-up	The phase began with flexion at the knees, primarily in the lead leg. As this flexion progressed, rotation at the hip and torso was performed bringing the lead shoulder away from the target. Horizontal flexion occurred with the rotation, tilting the torso to the lead leg. Abduction at the shoulder was performed by the attacking arm as the rotation is performed.
Initiation	The phase was primarily characterised by a reversal of the movements found in the wind-up. As extension was performed at the lead foot, knee, and hip, the torso rotated and horizontally flexes bringing the lead shoulder towards the target. Throughout the phase, the attack arm extended and continued to abduct at the shoulder preparing for execution.
Execution	As the torso continued to rotate, the attacking arm flexed at the elbow and horizontally adducted at the shoulder. At the feet, a small jump or bilateral foot rotation (lead foot internally and rear foot externally) was performed, further moving the lead shoulder anterior and medial to the target. The arm reaches the final abducted position before impact.
	RHH
Wind-up	The RHH follow the same basic pattern as the LHH. Similar flexion at the knees occurred, with rotation and horizontal flexion at the hip and torso. This rotation and horizontal flexion was directed to the rear leg in this case. Also differing from the LHH, a portion of the boxers started with a forward step similar to a cross punch before rotation was performed.
Initiation	Again, the RHH is essentially a mirror of the LHH. The reversal of the rotation and horizontal flexion was performed with extension at the rear leg rather than the front leg. Similarly, rotation at the hip occurred at the rear leg. The rear arm follows the same pattern as the LHH.
Execution	Differences continue from the LHH in this phase. As the stepping foot made contact or the lead leg flexed accepting weight, only the rear foot rotated (internally). This is far more like the cross than the LHH. The attacking arm continues to mirror the action found in the LHH.

Discussion

A clear pattern of punching emerged from the GRF data of ten experienced boxers that was consistent across the cohort. This pattern allowed for the identification of objective phases of punches, informed by triangulation of experienced boxing coaches (Lenetsky & Lindsay, 2017), experts in striking based combat sports, and an experienced biomechanist. Using the newly defined phases, a greater understanding of muscle activation patterns was possible by integrating EMG data. Finally, the phases were used to establish a qualitative understanding of the jab, cross, LHH, and RHH visually.

Beyond identifying the phases of the punches examined, the GRF results provided qualitative findings that contributed to the knowledge of punching. A general propulsion forward was found at the target in both straight punches (jab and cross). Whereas in the hook punches the propulsion was more lateral, but still included some forward movement towards the target. As straight punches were performed from a farther distance than the hooks, a closing of distance with forward movement was needed to reach attacking range and potentially maximise punching impact kinetics. In both types of punches the propulsion to the target was counteracted by forces away from the target produced by the leg contralateral to the punching arm. The net force does not create equilibrium as there was a clear movement forward towards the target found in the visual analysis. This counter force appears to act similar to a “block”, a movement seen in throwing sports (Morriss, Bartlett, & Navarro, 2001). This block has been theorised to increase hip velocities (Morriss & Bartlett, 1996), and could be a key component in effective punching. Hip rotation velocity has been explored in boxing (Cheraghi et al., 2014), and has been linked to punching performance (Cabral et al., 2010).

The EMG data from our cohort found the DPMA pattern clearly in the triceps. DPMA was seen as well in the RRF during the RHH, but this pattern was not as clear as seen in the triceps. A unique finding in this study was the apparent triple peak activation pattern found during the LHH in the LLD. Similar findings have been reported during kicking (McGill et al., 2010), but to the authors knowledge this is the first time it has been found in analysis of a punch. From the placement of the activity peaks, it appears that the first peak in the LLD aids in rotating the torso away from the target to pre-load the movement (the wind-up rotation seen in the visual analysis), then peaks later to stabilise the torso as the RLD brings the torso around into an attack position, and then finally reaches a maximal peak to reduce compliance at impact. A peak at the end of the impact phase was found repeatedly in the triceps and latissimus dorsi of the attacking arm during punches. This result fits current DPMA theories as a mechanism to stiffen the upper body, thus reducing compliance (Lenetsky et al., 2015). Differing from current theories, the peak found in the latissimus dorsi at the end of impact was foreshadowed by activation on the contralateral side, producing in effect, DPMA across the body. The activation of the contralateral latissimus dorsi initiates rotation, followed by relaxation, and then activation of the punching side latissimus dorsi at impact to potentially enhance effective mass. It is unknown if this method produces greater effective mass at impact, as the role of the latissimus dorsi in punching is not well established and further research is needed to explain this finding.

From the GRF and EMG findings a clear structure of punching movements in boxers can be established. The visual analysis serves to further clarify understanding of punching, giving context to the results. At its essence, straight and hook punching are full body rotations, initiated by the lower body, producing torque through the hips and up the kinetic chain through the fist and into the target. During this rotation, the muscles activated sequentially from the ground up (Cabral et al., 2010), working in concert to maximise velocity and stiffness during impact.

The following chapter will use the structure of phases developed in this manuscript to produce clarity in the terminology of punching in boxing. Furthermore, the qualitative findings of this study need quantitative research to establish a more complete understanding of punching. Specifically, the role of GRF and EMG patterns in maximising punching impact kinetics, the influence of EMG timing in effective punching, and the differences in GRF and EMG results found in other styles of combat sport punching.

Conclusions

The definition of phases for the jab, cross, LHH, and RHH in boxing provides a context for coaches and sport science practitioners to better communicate. A coach can use this information to identify the exact phase they see a fighter needing improvement and can communicate that with a sport science practitioner to explore the issue in a multi-faceted manner. With the constant need for bridging the gap between coaching and sport science (Buchheit, 2017), such tools for improving communication are crucial. In efforts to maintain the bridging of these disciplines, we chose to use the information collected from experienced boxing coaches to structure our analysis of punching. It is our hope that effort on our part will further aid in the holistic training and assessment of boxers. Additionally, the qualitative findings from our results provide valuable insights into punching, but without quantitative data at this time, the authors recommend these findings are used with consideration.

CHAPTER 8 a & b

GROUND REACTION FORCE AND ELECTROMYOGRAPHIC DETERMINANTS OF PUNCHING IMPACT KINETICS IN MALE BOXERS

Reference

Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Ground reaction force determinants of punching impact kinetics in male boxers. *International Journal of Sports Physiology and Performance*, In prep.

Lenetsky, S., Brughelli, M., Nates, R.J., Neville, J.G, Cross, M.R., & Lormier, A.V. (2018). Electromyographic determinants of punching impact kinetics in male boxers. *Scandinavian Journal of Medicine & Science in Sport*, In prep.

Author contribution

SL: 80%, MB: 5%, RJN: 5%, JGN: 5% MRC: 2.5%, AVL: 2.5%

Preface

This chapter of the thesis combines the novel findings from all the previous chapters into a study of the determinants of impact kinetics in punching. The chapter is focused on the potential keys to effective punching, GRF and muscle activation, both variables identified in Section 1. Impact dynamometry was performed with the method developed in Section 2. The phases defined in Chapter seven were used as a framework to provide insight into the action of punching at a micro-level and to discriminate key variables at the macro-level. This final chapter serves as the first study to establish any determinant of punching performed in situ.

Abstract

The impact kinetics of punches are currently theorised to be crucial factors of boxing performance. Literature focused on boxing and other striking based combat sports have explored many aspects of punching, the findings of which have highlighted the role of neuromuscular activation patterns and ground reaction forces as potential key determinants of punching impact kinetics. However, there is a paucity of research exploring in situ methods that boxers employ to develop impact kinetics. To explore this gap in the literature, a cross sectional study of ten expert male boxers was performed to identify the key determinants of impulse, effective mass, peak and mean force during the impact of punches. Striking dynamometry, electromyography, and ground reaction forces were collected during four different punch types; the jab (a lead hand straight punch), cross (a rear hand straight punch), lead hand hook and rear hand hook to provide the necessary data. Statistical analysis via hierarchical regression was used to identify the key determinants of impact kinetics. The determinant findings established not only the uniqueness of each punch type, but also of each impact variable. Although, general trends did appear to be consistent in the observed boxing punches. These trends focused on the lower body's contribution as the key determinant, supported by contribution from the core muscles, and the need of the upper body to remain relaxed through the punching action. The findings from this study provide original quantitative evidence supporting current theories in the literature (primarily the importance of the lower body), evidence conflicting with other theories (double peak muscle activation relationship to effective mass), and provide a new fundamental understanding of punching in boxing, solidify.

Introduction

Current theories into punching performance have identified impact kinetics as key determinants of boxing performance (Lenetsky et al., 2013; Lenetsky et al., 2015). Research into striking based combat sports, including boxing, have explored aspects of punching, including the kinematics (Cabral et al., 2010; Cheraghi et al., 2014; P. Girodet et al., 2005; Neto et al., 2012; VencesBrito et al., 2011) and the kinetics (Loturco et al., 2015; Neto et al., 2007; Pierce et al., 2006;

Turner et al., 2011; Walilko et al., 2005). However, there is a paucity of studies investigating the methods boxers, and other combat sports athletes, employ to improve punching impact kinetics (Lenetsky et al., 2013). The few studies that have explored training effects on punching performance have identified potential insights into the components of effective punching. Studies investigating the effects of improved lower and upper body strength in boxers have found increases in mean punching force (Stanley, 2014). Additionally, correlations have been found between lower and upper body strength and power measures, and peak punching force (Loturco et al., 2015). Isometric and dynamic core strengthening has been found to increase peak striking force through specific muscle activation patterns (Lee & McGill, 2016). These findings have focused on the role of neuromuscular activation patterns and ground reaction forces (GRF) that play as key determinants of punching impact kinetics.

Results of strength training interventions indicate that muscular strength plays a role in effective punching, with lower body strength contributing more to punching impact kinetics than the upper body (Loturco et al., 2014; Loturco et al., 2015). Conclusions from a review on contributors to punching impact kinetics reinforces these findings, finding that lower body contribution (GRF) during the punch is a paramount component of punching performance (Lenetsky et al., 2013). The review notes the role GRF plays in other sports and a study by Filimonov and colleagues (Filimonov et al., 1983), found the greater the lower body contribution to punching the greater the punching force of the boxer. A qualitative investigation into what factors boxing coaches deem of most importance for effective punching concurred with the quantitative findings (Lenetsky & Lindsay, 2017). Results of the study found that all coaches interviewed placed the lower body's role in punching as the primary factor in success. Despite this agreement on the lower body's role in effective punching there exists little in the literature linking GRF or any other variables produced by the lower body directly to punching impact kinetics.

The role of GRF in punching is not the sole theory currently in the literature thought to be of great importance for punching performance. Double peak muscle activation (DPMA) as proposed by McGill and colleagues (2010), is thought to be used to increase punching impact kinetics, particularly effective mass. Effective mass has been described as a measure of an athlete's inertial contribution to impact (Lenetsky et al., 2015). DPMA is composed of an initial activation beginning the punching motion, relaxation allowing for an increase in punch velocity due to the mechanical nature of muscle (McGill et al., 2010), and then a final activation increasing stiffness upon impact. While this theory is commonly presented in literature, no published studies have explored the quantitative relationship between DPMA and effective mass, or any other impact variables.

The current state in the literature provides valuable insights into punching performance, but leave researchers and practitioners alike without a clear understanding of which key determinants of punching kinetics to focus on. This study will establish the role of both muscle activation patterns and GRF in the determination of impact kinetics as performed by a cohort of experienced boxers.

Methods

Participants

Ten experienced and competitive amateur and professional male boxers (age = 25.6 years ± 5.97, height = 179.5 cm ± 7.72, weight = 95.66 kg ± 21.82, and years training = 10.3 years ± 5.97) participated in this study. 'Experienced' was defined as having three or more years of training in boxing and 'competitive' was defined as having a bout either in the three months preceding or following the assessment. Data collection protocols were explained to all participants and all signed acknowledgement of informed consent before data collection commenced. All procedures were approved by the Auckland University of Technology Ethics Committee (12/332) for this study.

Design

This study seeks to investigate the relationship between GRF, electromyographic (EMG) data and results of punching impact kinetics in a cohort of experienced boxers. A cross sectional design was implemented to identify key determinants of impulse, effective mass (a measure of a boxer's inertial contribution to impact (Lenetsky et al., 2015)), peak and mean force during impact. Four punch types were assessed during data collection; the jab (a lead hand straight punch), cross (a rear hand straight punch), a lead hand hook and a rear hand hook. Assessment of the punches was performed in a single data collection fitting within the boxer's normal training schedule.

Methodology

Konrad's (2006) protocols were followed for preparation and placement of electrodes for EMG collection. All participants were prepared for electrode placement bi-laterally on the triceps brachii (LTB and RTB), latissimus dorsi (LLD and RLD), rectus abdominis (LRA and RRA) and rectus femoris (LRF and RRF) of the lead and rear sides. Electrode locations were prepared by shaving to remove excess hair, abraded, and cleaned with alcohol. After application of electrodes (Duo-Trodes, Myotronics, Australia), electrical resistance was tested for a threshold of 10 kΩ (Konrad, 2006), any electrode with a resistance higher above 10 kΩ was removed and preparation was repeated until findings were below the standardised threshold. After electrode preparation, participants performed a standardised warm-up consisting of 5 minutes of moderate intensity cardiovascular exercise (no more than a 5 rate of perceived exertion on a modified Borg scale (Borg, 1982)) and dynamic stretches. After the general warm-up, maximal voluntary isometric contractions (MVIC) were performed by the participants on all applicable muscles following an established protocol (Konrad, 2006).

Post MVIC testing, all participants undertook a boxing specific warm-up (shadow boxing) and familiarisation strikes of each punch type (jab, cross, lead hand hook [LHH], and rear hand hooks [RHH]) on a striking bag (NZ Boxer, Teardrop style, Auckland). Seven repetitions of each strike type were performed against the standard striking bag for data collection. The last five of the seven punches were used for analysis, as per Lenetsky et al. (2017), to remove erroneous results caused by the deformation of the bag. Each punching trial was executed maximally with a minimum of one-minute rest between each effort. Boxers self-select specifics of the technique and range from the striking bag in an effort to maximize performance (Halperin et al., 2016).

Phases of punching in boxing

Recently, data from a cohort of boxers were used to establish the phases of movement for straight and hook punches (Lenetsky, Brughelli, et al., 2017). These phases were based off of specific events found in the GRF data and were used to develop the phases found in Table 1. After collection and filtering of the GRF data from in this study, the data were processed using a custom MATLAB programme to identify each phase. This information was then used in the statistical analysis of the results.

Table 17. Phases of punching in boxing established by Lenetsky et al. (2017).

Jab	Cross	LHH	RHH
Initiation	Initiation	Wind-Up	Wind-Up
Execution	Execution	Initiation	Initiation
Impact	Impact	Execution	Execution
		Impact	Impact

Equipment

All participants were provided with standardised boxing gloves (NZ Boxer Boxing Gloves 16oz, NZ Boxer, Auckland, New Zealand) and hand wraps (NZ Boxer 2.5m Hand Wraps, NZ Boxer, Auckland, New Zealand). Trials were recorded with an 8 channel EMG system (AMT-8 “Octopus”, Bortec Biomedical Ltd., Calgary, Canada) collecting muscle activation data, GRF data were collected via two force plates (Accupower, Advanced Mechanical Technology, Inc., Wattertown, MA, United States) one plate under each leg, and impact kinetics were measured with Lenetsky et al.’s (2017) method of striking dynamometry using a tri-axial accelerometer (Model 4630A, Measurement Specialties, Aliso Viejo, CA, United States); all devices sampled at 1000 Hz. A high-speed video (HSV) camera (A602fc-2, Basler, Germany) was used to collect visual data (200 Hz sampling rate). Data from the force plates, EMG system, HSV, and striking dynamometer were time synchronized through a VICON system (Version 1.7, VICON Inc., Denver, CO, United States). A second HSV camera (EOS 5D Mark 3, Canon, Japan) collecting at 200hz was used to confirm impact on the designated target. Punches that did not land on the target were discarded from the final analysis and trials were repeated until seven successful punches had been recorded. This collection method was employed as punches that missed the target would alter the impact kinetic results (Lenetsky, Nates, et al., 2017). Previous testing had determined that two impacts were required to deform the striking bag to the point where compression would no longer affect readings, consequently, the first two punches performed of each type were removed from the analysis (Lenetsky, Nates, et al., 2017).

GRF data was filtered with a 100 Hz low pass Butterworth filter and analysis was performed with a custom MATLAB programme (R2016a, MathWorks, Natick, MA, United States) to identify key variables and normalised to body weight. EMG data were processed with a custom MATLAB programme as well, filtered with a band pass Butterworth filter (10 - 450 Hz), full wave rectified, and a low pass Butterworth filter (3 Hz) was applied to produce a linear envelop following current guidelines and previous literature exploring punching EMG data (Lee & McGill, 2016; McGill et al., 2010; Merletti & Di Torino, 1999). The processed EMG data were normalised to the MVIC data for final analysis. EMG activation was determined using a threshold of 10% of the participants MVIC. Magnitude and timing of peak EMG was recorded for each activation period. Impact kinetic data were calculated with a custom LabVIEW programme (Version 11.0, National Instruments Corp., Austin, TX, USA) to calculate absolute impulse, peak and mean force before the data were normalised to body weight for analysis. All GRF and EMG data was temporally normalised around impact data for cross comparison of each punch. Analysis of the 2D HSV was performed using a Kinovea software package (Version 0.8.15) to determine pre-impact punch velocity of the jab and cross trials only. This was due to the multi-plane movement of the hook punches, which would not suit 2D HSV analysis. The pre-impact velocity was used to calculate effective mass as developed by Neto et al. (2012) and seen in equation 20. In equation 1, $M_e$is effective mass, Imp is impulse taken from the striking dynamometer, and S is the pre-impact velocity measured from the HSV.

$$M_e = \frac{Imp}{S}$$

Equation 20.

Statistical analysis

Variables of interest for this analysis were maximal and minimal GRF values, maximal positive and negative rates of GRF development, peak activation, number of activation peaks, and temporal activation patterns (time of peak activation, phase of peak activation, duration of activation, phase in which the start and end of activation occurred); all produced during the four punch types. These definitions and abbreviations for all independent variables are found in Table 18.

Table 18. Definitions and abbreviations of the independent variables.

Independent Variable	Abbreviation	Definition
Maximal GRF	*Max GRF*	Maximal GRF value found during a given phase in Newtons per kilogram of body weight.
Minimal GRF	*Min GRF*	Minimal GRF value found during a given phase in Newtons per kilogram of body weight.
Maximal positive GRF development	*GRFDpos*	Value of the steepest positive slope.
Maximal negative GRF development	*GRFDneg*	Value of the steepest negative slope.
Peak Activation	*Peak*	Peak value in MVIC normalised units.
Number of Activation Peaks	*Number of peaks*	Total number activations and their corresponding peak per punch.
Time to Peak Activation	*Time to peak*	Time in seconds from the beginning of the activation to the peak value.
Phase of Peak Activation	*Phase Peak*	The phase in which the peak value occurs.
Duration of Activation	*Duration*	Duration (seconds) of the activation in which the peak value is found.
Phase of Activation Start	*Phase Start*	The phase in which the peak value activation begins.
Phase of Activation End	*Phase End*	The phase in which the peak value activation ends.

A hierarchical regression using magnitude-based inference was employed to identify the determinants of impulse, effective mass, peak (Fmax) and mean (Fmean) force from the above independent variables. This method, developed by Brown et al. (2016), allowed for a discriminatory process identifying only paramount variables with detailed interpretations of the findings. Unique to this paper, the phases of punching were integrated into the hierarchical model for the analysis of the GRF results. Correlation matrices were first created and analysed comparing each phase to the impact variables, then the identified key variables from all of the phases were analysed in the same method for the impact variables of the punch type as a whole. The EMG results did not suit the usage of the phase model and instead were analysed only by the dependent variable and punch type. The key determinates from the GRF and EMG results were then entered in another set of matrices for the final analysis.

First in the hierarchical process, variance inflation factor (VIF > 5) was used to identify variable(s) that contributed to collinearity. This process was followed by checks for multicollinearity (Pearson r ≥ 0.8) between independent variables (Ardern, Taylor, Whitehead, & Webster, 2013). After the removal of collinear variables, the remaining variables were entered into a new matrix where they were correlated with the dependant variables (impulse, effective mass, peak and mean force) individually. Descriptive statistics of mean and standard deviation or median and min/max quantiles were produced for each variable. As well, Pearson correlation coefficient (r) and co-efficient of determination (r^2) were calculated for each model. Thresholds used for interpreting the mechanistic importance of each variable correlations were < 0.10 (trivial), 0.10 (small), 0.30 (moderate), 0.50 (large), 0.70 (very large), 0.90 (nearly perfect) and 1.0 (perfect) correlations (Hopkins et al., 2009). Only moderate or higher (≥ 0.3) correlations were considered appropriate for the subsequent multiple regression equations. A 5:1 ratio of boxers to independent variables (10 boxers = maximum of two independent variables) were implemented to account for shrinkage and inflated error rates due to the study's smaller sample size (Alii, 2010). An example of this process can be seen in Figure 19.

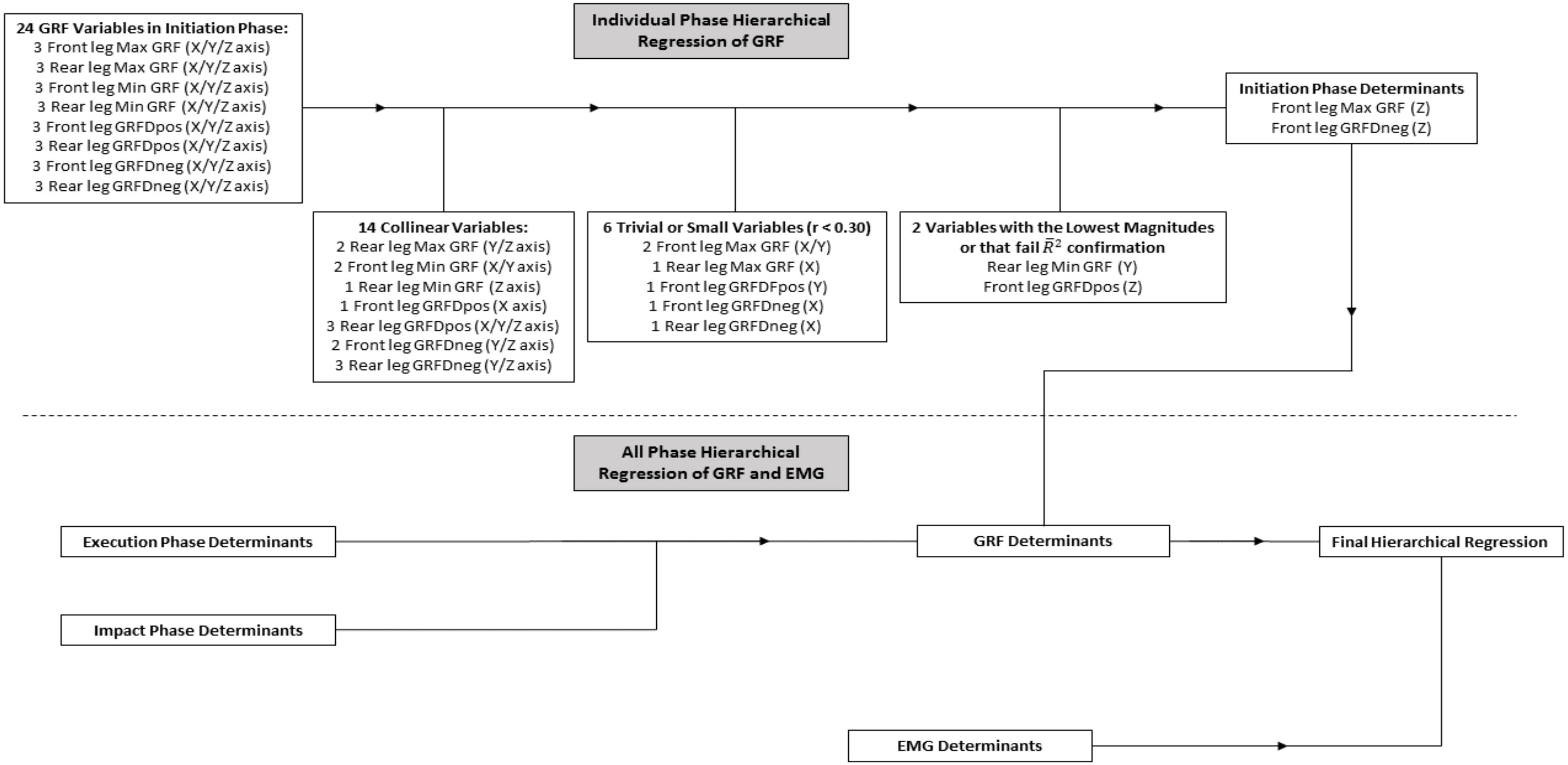


Figure 19. An example of the hierarchical regression process as performed on the cross punch for the impulse variable.

After the above criteria were used to determine independent variables continuing in the hierarchical regression model, the $\bar{R}^2$ of each variable was evaluated to confirm that the influence of the variables was not random. If the inclusion of a new independent variable decreased the $\bar{R}^2$, the real contribution was less than what would be produced by chance, and as such was removed from the final equation. Inferences based on the square-root of the $\bar{R}^2$ were presented for the remaining variables in the model to describe the magnitude of the observed relationship (Brown, 2016). All statistical analyses were performed in JMP Statistical Analysis System (version 13, SAS Institute Inc., Cary, NC, US).

Results

All findings are the final results of the hierarchical regression process explained in the statistical analysis section. As explained above, key determinants of punching impact kinetics were first established for the GRF and EMG results separately before a final model was created with a combination of all relevant independent variables. Variables of interest and those with commonality between impact kinetics are noted in the text below.

GRF results

GRF determinants of impact kinetics ($\bar{R}^2$ and magnitude based inferences) and descriptive statistics (mean, standard deviation, r, and r^2) are presented for each punch type in Tables 19 through 22.

Table 19. GRF determinates of impact kinetics in the jab punch.

	Phase	Variable	Mean	SD	r	r^2	$\bar{R}^2$	Inference
Impulse	2	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.49	0.24	0.22	Moderate
	3	Min Rear Leg Y Axis	-7.89	30.89	-0.48	0.23	0.21	Moderate
	3	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.41	0.08	0.06	Small
		Key Determinates						
	1	Min Rear Leg Z Axis	-1492.62	354.26	0.61	0.37	0.36	Large
	2	GRFDneg Rear Leg Z Axis	606.34	580.52	-0.49	0.24	0.22	Moderate
Fmax	1	Min Rear Leg X Axis	-308.06	78.31	0.53	0.28	0.27	Large
	2	Max Rear Leg Z Axis	-123.66	128.86	0.54	0.29	0.27	Large
	2	Min Rear Leg X Axis	-309.22	81.58	0.53	0.28	0.26	Large
		Key Determinates						
	3	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.60	0.36	0.34	Large
	3	Min Rear Leg Y Axis	-7.89	30.89	-0.59	0.35	0.34	Large
Fmean	1	Min Rear Leg X Axis	-308.06	78.31	0.59	0.35	0.33	Large
	1	GRFDneg Rear Leg Z Axis	-10730.6	3428.26	0.43	0.18	0.17	Moderate
	2	Min Rear Leg X Axis	-309.22	81.58	0.58	0.46	0.45	Large
	2	Max Rear Leg Z Axis	-123.66	128.86	0.49	0.01	-0.01	Trivial
		Key Determinates						
	3	Min Rear Leg Y Axis	-7.89	30.89	-0.54	0.29	0.28	Large
	3	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.52	0.27	0.26	Large
Effective Mass	1	Max Lead Leg Y Axis	50.40	48.83	0.33	0.11	0.09	
	2	Max Lead Leg Y Axis	25.59	36.01	0.32	0.10	0.08	Small
	3	Min Rear Leg Y Axis	-7.89	30.89	-0.31	0.10	0.08	Small
		Key Determinates						
	3	Min Lead Leg X Axis	31.14	67.53	-0.48	0.23	0.21	Large
	2	GRFDpos Lead Leg Y Axis	1608.8	1317.64	-0.41	0.17	0.15	Moderate

Phases are identified as follows: 1 = initiation, 2 = execution, and 3 = impact

Minimal Y axis findings from the multiple phases had large negative relationships with Fmax (r = -0.59 and $\bar{R}^2$ = 0.34) and Fmean (r = -0.54 and $\bar{R}^2$ = 0.28) during the jab. Negative correlations were also found between the rear leg GRFDpos in the Z axis with Fmax (r = -0.60, $\bar{R}^2$ = 0.34, and a large inference) and Fmean (r = -0.52, $\bar{R}^2$ = 0.26, and a large inference). Key determinants of impulse and effective mass measures did not have any similarities between each other or Fmax and Fmean.

Table 20. GRF determinates of impact kinetics in the cross punch.

	Phase	Variable	Mean	SD	r	r^2	$\bar{R}^2$	Inferenc
Impulse	1	GRFDpos Lead Leg Z Axis	6077.73	3157.83	0.53	0.28	0.26	Larg
	1	Min Rear Leg Y Axis	64.11	56.65	-0.52	0.27	0.25	Larg
	2	Max Lead Leg Z Axis	-457.34	200.62	0.80	0.64	0.63	Ver Larg
	3	GRFDneg Lead Leg X Axis	-1044.28	1612.64	-0.60	0.36	0.35	Larg
		Key Determinates						
	3	Max Lead Leg Z Axis	-417.44	237.7	0.88	0.77	0.77	Ver Larg
	2	GRFDneg Lead Leg Z Axis	657.1	3286.22	0.64	0.51	0.50	Ver Larg
Fmax	1	Min Rear Leg X Axis	-146.22	48.55	0.50	0.24	0.22	Moderat
	2	Max Lead Leg Z Axis	-457.34	200.62	0.62	0.38	0.37	Larg
	2	GRFDneg Lead Leg Z Axis	657.10	3286.22	0.55	0.3	0.29	Larg
	3	Max Lead Leg Z Axis	-417.44	237.70	0.69	0.48	0.46	Larg
		Key Determinates						
	3	GRFDneg Lead Leg Z Axis	-6689.09	8153.62	0.63	0.40	0.39	Larg
	1	Min Lead Leg Z Axis	-908.29	210.32	0.64	0.26	0.24	Moderat
Fmean	1	Min Lead Leg Z Axis	-908.29	210.32	0.64	0.29	0.27	Larg
	1	Min Rear Leg X Axis	-146.22	48.55	0.50	0.33	0.31	Larg
	2	Max Lead Leg Z Axis	-457.34	200.62	0.66	0.43	0.42	Larg
	2	GRFDpos Rear Leg Z Axis	9298.34	4493.95	-0.33	0.11	0.09	Moderat
		Key Determinates						
	3	Max Lead Leg Z Axis	-417.44	237.7	0.72	0.52	0.51	Ver Larg
	3	GRFDneg Lead Leg Z Axis	-6689.09	8153.62	0.67	0.44	0.43	Larg
Effective Mass		No variables met criteria						

Phases are identified as follows: 1 = initiation, 2 = execution, and 3 = impact

Vertical loading (Z axis) of the lead leg had large to very large positive relationships with impulse (r = 0.88 and $\bar{R}^2$ = 0.77), Fmax (r = 0.64 and $\bar{R}^2$ = 0.24), and Fmean (r = 0.72 and $\bar{R}^2$ = 0.51) during the initiation and impact phases of the cross. Similarly, GRFDneg of vertical forces in the lead leg had large to very large influences on impulse (r = 0.64 and $\bar{R}^2$ = 0.50), Fmax (r = 0.63 and $\bar{R}^2$ = 0.39), and Fmean (r = 0.67 and $\bar{R}^2$ = 0.43). No independent variables met the criteria of inclusion as a key determinant of effective mass through the hierarchical regression process.

Table 21. GRF determinates of impact kinetics in the LHH punch.

	Phase	Variable	Mean	SD	r	r^2	$\overline{R}^2$	Inferen
Impulse	1	Min Lead Leg Z Axis	-847.12	216.31	0.37	0.13	0.12	Modera
	3	Max Rear Leg Y Axis	-2.48	34.48	-0.38	0.14	0.13	Modera
	4	Min Rear Leg X Axis	-51.30	40.57	-0.35	0.12	0.11	Modera
	4	Max Rear Leg Y Axis	21.80	46.27	-0.34	0.12	0.10	Modera
		Key Determinants						
	3	Min Rear Leg X Axis	-150.22	85.51	0.43	0.18	0.16	Modera
	2	Min Rear Leg Z Axis	-606.22	295.91	0.42	0.18	0.16	Modera
Fmax	4	Min Lead Leg Y Axis	-55.77	60.51	-0.35	0.12	0.10	Modera
	4	GRFDneg Rear Leg Y Axis	-610.16	2053.72	-0.33	0.11	0.09	Modera
		Key Determinants						
	3	GRFDneg Rear Leg X Axis	-530.12	847.2	-0.54	0.29	0.28	Lar
	3	Min Rear Leg X Axis	150.22	85.51	0.45	0.20	0.18	Modera
Fmean	1	Min Lead Leg Z Axis	126.25	54.79	0.45	0.20	0.19	Modera
	1	Max Rear Leg Y Axis	-847.12	216.31	-0.31	0.10	0.08	Sma
	2	Min Rear Leg Z Axis	-606.22	295.91	0.41	0.17	0.15	Modera
	4	GRFDneg Rear Leg Y Axis	-610.16	2053.72	0.30	0.09	0.07	Sma
		Key Determinants						
	3	GRFDneg Rear Leg X Axis	-824.45	1444.8	-0.50	0.25	0.23	Modera
	4	Max Rear Leg Y Axis	21.80	46.27	0.46	0.21	0.19	Modera

Phases are identified as follows: 1 = wind-up, 2 = initiation, 3 = execution, and 4 = impact

Common key determinants of the LHH include Min X axis GRF and GRFDneg in the rear leg during the execution phase. Min rear leg X axis was a key determinant of impulse (r = 0.43, $\overline{R}^2$ = 0.16, and a moderate inference) and Fmax (r = 0.45, $\overline{R}^2$ = 0.18, and a moderate inference). GRFDneg of the rear leg in the X axis was a key determinant of Fmax (r = 0.54, $\overline{R}^2$ = 0.28, and a large inference) and Fmean (r = -0.50, $\overline{R}^2$ = 0.23, and a moderate inference). All other key determinants were individual to specific impact kinetics.

Table 22. GRF determinates of impact kinetics in the RHH punch.

Phase		Variable	Mean	SD	r	r^2	$\bar{R}^2$	Inferen
Impulse	1	Max Rear Leg Y Axis	216.31	74.22	-0.46	0.21	0.19	Modera
	2	Min Lead Leg X Axis	-123.49	59.23	0.35	0.12	0.10	Modera
	2	Min Rear Leg Z Axis	-949.08	247.81	0.30	0.09	0.07	Sma
	3	Max Lead Leg Z Axis	-351.51	192.56	0.41	0.17	0.15	Modera
		Key Determinants						
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	-0.69	0.48	0.47	Lar
	1	Max Rear Leg Z Axis	-473.76	101.66	0.47	0.22	0.20	Modera
Fmax	2	GRFDneg Rear Leg X Axis	-1111.94	1218.67	-0.41	0.17	0.15	Modera
	2	GRFDneg Rear Leg Z Axis	7857.32	4117.26	-0.33	0.11	0.09	Sma
	3	Max Rear Leg Y Axis	172.41	56.49	0.34	0.12	0.10	Modera
	3	Max Lead Leg Z Axis	-351.51	192.56	0.30	0.09	0.07	Sma
	4	GRFDpos Lead Leg Z Axis	704.10	3372.15	0.32	0.10	0.08	Sma
		Key Determinants						
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	0.62	0.38	0.37	Lar
	1	Max Rear Leg Z Axis	-473.76	101.66	0.53	0.28	0.26	Lar
Fmean	1	Max Rear Leg Y Axis	216.31	74.22	-0.43	0.24	0.23	Modera
	2	Max Rear Leg Z Axis	-507.79	213.47	0.33	0.11	0.09	Modera
	2	GRFDpos Rear Leg Z Axis	7857.32	4117.26	-0.30	0.09	0.07	Sma
	3	Max Lead Leg Y Axis	11.97	76.49	-0.39	0.15	0.14	Modera
	3	GRFDneg Rear Leg Z Axis	-110.96	1679.76	0.36	0.13	0.11	Modera
	4	Min Lead Leg Y Axis	6.02	75.54	-0.40	0.16	0.14	Modera
		Key Determinants						
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	-0.67	0.45	0.44	Lar
	1	Max Rear Leg Z Axis	-473.76	101.66	0.68	0.46	0.45	Lar

Phases are identified as follows: 1 = wind-up, 2 = initiation, 3 = execution, and 4 = impact

Above all other punch types, the RHH had the most commonality between key determinants. All impact kinetics had moderate to large positive relationships with max rear leg loading in the Z axis (impulse – r = 0.47 and $\bar{R}^2$ = 0.20, Fmax – r = 0.53 and $\bar{R}^2$ = 0.26, and Fmean – r = 0.68 and $\bar{R}^2$ = 0.45). X axis GRFDneg in the lead leg as well had large magnitude relationships with all impact kinetics, but Fmax and Fmean had a positive correlation (Fmax – r = 0.62 and $\bar{R}^2$ = 0.37), while impulse and Fmean both had negative correlations (impulse – r =- 0.69 and $\bar{R}^2$ = 0.77 and Fmean – r = -0.67 and $\bar{R}^2$ = 0.44).

EMG Results

EMG descriptive statistics (mean and standard deviation, median and min/max quantiles [when appropriate for the variable], r, and r^2) and determinants of impact kinetics ($\bar{R}^2$ and magnitude based inferences) are found in Tables 23 through 26.

Table 23. Muscle activation determinates of impact kinetics in the jab punch.

	Muscle Group	Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	LRA	Peak	0.22	0.11	0.38	0.15	0.12	Moderate
	RRF	Phase Peak	1*	1/Post*	-0.45	0.2	0.19	Moderate
	LRF	Peak	0.54	0.29	0.34	0.12	0.09	Moderate
	RLD	Peak	0.61	0.29	0.42	0.18	0.15	Moderate
	LLD	Peak	0.54	0.35	- 0.48	0.23	0.21	Moderate
	RTB	Duration	0.41	0.12	-0.47	0.22	0.20	Moderate
	RTB	Phase Start	1*	Pre/2*	0.35	0.12	0.10	Moderate
	LTB	Phase End	Post*	2/Post*	0.47	0.23	0.21	Moderate
		Key Determinates						
	LLD	Phase Start	1*	Pre/Post*	0.63	0.40	0.38	Large
	LTB	Number of Peaks	1.30	0.55	0.45	0.20	0.19	Moderate
Fmax	RRA	Duration	0.33	0.13	0.33	0.11	0.08	Small
	LRA	Peak	0.22	0.11	0.42	0.18	0.15	Moderate
	RRF	Phase of Peak	1*	1/Post*	-0.50	0.25	0.23	Moderate
	RRF	Time to Peak	0.21	0.12	-0.45	0.21	0.19	Moderate
	LRF	Peak	0.54	0.29	0.48	0.23	0.21	Moderate
	RLD	Peak	0.61	0.29	0.39	0.15	0.13	Moderate
	RLD	Phase Start	1*	Pre/2*	-0.36	0.13	0.10	Moderate
	LLD	Peak	0.54	0.35	-0.47	0.22	0.20	Moderate
	RTB	Duration	0.41	0.12	-0.46	0.21	0.19	Moderate
	RTB	Phase Start	1*	Pre/2*	0.35	0.12	0.10	Moderate
	LTB	Phase End	Post*	2/Post*	0.53	0.29	0.26	Large
	LTB	Number of Peaks	1.3	0.55	0.45	0.21	0.19	Moderate

		Key Determinates						
	LLD	Phase Start	1*	Pre/Post*	0.61	0.37	0.35	Large
	LRF	Phase Start	1*	Pre/2*	-0.32	0.10	0.08	Small
Fmean	LRA	Peak	0.22	0.11	0.39	0.16	0.13	Moderate
	RRF	Phase of Peak	1*	1/Post*	-0.50	0.25	0.23	Moderate
	RRF	Time to Peak	0.21	0.12	-0.39	0.15	0.13	Moderate
	LRF	Peak	0.54	0.29	0.42	0.18	0.15	Moderate
	RLD	Peak	0.61	0.29	0.39	0.15	0.13	Moderate
	LLD	Phase Start	1*	Pre/Post*	0.61	0.37	0.36	Large
	LLD	Peak	0.54	0.35	-0.53	0.28	0.26	Large
	LTB	Phase End	Post*	2/Post*	0.52	0.27	0.25	Large
		Key Determinates						
	LTB	Number of Peaks	1.30	0.55	0.50	0.25	0.23	Moderate
					-			
	RTB	Duration	0.41	0.12	0.48	0.23	0.22	Moderate
Effective Mass	RRA	Phase of Peak	2*	1/Post*	-0.32	0.11	0.09	Moderate
	LRA	Peak	0.22	0.11	0.51	0.26	0.23	Moderate
	LRA	Phase End	Post*	2/Post*	0.43	0.19	0.16	Moderate
	RRF	Phase Peak	1*	1/Post*	-0.42	0.18	0.16	Moderate
	RRF	Peak	0.67	0.4	0.33	0.11	0.09	Moderate
	LRF	Peak	0.54	0.29	0.47	0.22	0.20	Moderate
	LLD	Phase Start	1*	Pre/Post*	0.45	0.20	0.18	Moderate
	LTB	Phase End	Post*	2/Post*	0.46	0.21	0.19	Moderate
		Key Determinates						
	RTB	Duration	0.41	0.12	-0.51	0.26	0.24	Moderate
	RTB	Phase Start	1*	Pre/2*	0.41	0.17	0.15	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics.

In the jab, the phase of activation start was positively correlated to all impact kinetics except for Fmean. Phase start of the LLD had a moderate magnitude relationship with impulse (r = 0.47 and $\overline{R}^2$ = 0.21). LLD also had large relationships with Fmax (LLD – r = 0.61 and $\overline{R}^2$ = 0.35), and RTB had a moderate magnitude relationship with effective mass (r = 0.41 and $\overline{R}^2$ = 0.15). All phase start determinants had a median activation start during the wind-up phase of the punch.

Table 24. Muscle activation determinates of impact kinetics in the cross punch.

Muscle Group		Variable	Mean/Median	SD/Quantiles	r	r^2	$\overline{R}^2$	Inference
Impulse	RRA	Peak	0.29	0.15	0.38	0.15	0.12	Moderate
	RRA	Phase Start	Pre*	Pre/1*	0.37	0.14	0.11	Moderate
	LRA	Phase Start	Pre*	Pre/1*	0.43	0.19	0.16	Moderate
	RRF	Peak	0.61	0.46	-0.50	0.25	0.24	Moderate
	RLD	Peak	0.7	0.33	-0.60	0.36	0.35	Large
	LLD	Phase Peak	1*	1/Post*	-0.70	0.03	0.01	Small
	LLD	Duration	0.68	0.25	0.45	0.10	0.08	Small
	RTB	Number of peaks	1.25	0.48	-0.64	0.40	0.39	Large
	RTB	Phase Start	1*	Pre/Post*	0.63	0.04	0.02	Small
	LTB	Duration	0.43	0.21	0.72	0.52	0.51	Very Large
	LTB	Phase End	Post*	Pre/Post*	0.49	0.24	0.22	Moderate
	Key Determinates							
	RLD	Duration	0.46	0.17	-0.65	0.42	0.41	Large
	LRF	Number of peaks	1.51	0.59	0.50	0.25	0.24	Moderate
Fmax	RRA	Peak	0.29	0.15	0.46	0.21	0.18	Moderate
	RRA	Phase End	Post*	2/Post*	0.40	0.16	0.13	Moderate
	LRA	Phase Start	Pre*	pre/1*	0.56	0.33	0.31	Large
	RRF	Phase Start	Pre*	pre/1*	0.53	0.28	0.26	Large
	RRF	Peak	0.61	0.46	-0.37	0.13	0.11	Moderate

	LRF	Peak	0.98	0.42	0.51	0.26	0.24	Moderate
	LRF	Number of peaks	1.51	0.59	0.37	0.14	0.11	Moderate
	RLD	Peak	0.7	0.33	-0.71	0.50	0.49	Very Large
	LLD	Number of peaks	1.44	0.81	-0.33	0.11	0.09	Moderate
	RTB	Phase Start	1*	Pre/Post*	0.49	0.24	0.23	Moderate
	RTB	Number of peaks	1.25	0.48	-0.41	0.17	0.15	Moderate
	LTB	Phase End	Post*	Pre/Post*	0.51	0.26	0.24	Moderate
		Key Determinates						
	RLD	Phase Start	1*	Pre/2*	0.69	0.48	0.47	Large
	LTB	Duration	0.43	0.21	0.64	0.41	0.40	Large
Fmean	RRA	Phase Start	Pre*	Pre/1*	0.34	0.18	0.09	Moderate
	RRA	Phase End	Post*	2/Post*	-0.33	0.03	< 0.00	Trivial
	RRF	Peak	0.61	0.46	-0.38	0.15	0.13	Moderate
	LRF	Number of peaks	1.51	0.59	0.44	0.20	0.18	Moderate
	RLD	Duration	0.46	0.17	-0.68	0.47	0.45	Large
	RLD	Time to peak	0.23	0.10	-0.68	0.46	0.44	Large
	LLD	Duration	0.68	0.25	-0.38	0.15	0.13	Moderate
	RTB	Number of peaks	1.25	0.48	-0.57	0.32	0.31	Large
	RTB	Phase Start	1*	Pre/Post*	0.50	0.25	0.24	Moderate
	LTB	Duration	0.43	0.21	0.69	0.47	0.46	Large
	LTB	Time to peak	0.19	0.10	0.40	0.16	0.14	Moderate
		Key Determinates						
	LRA	Phase Start	Pre*	Pre/1*	0.57	0.32	0.30	Large
	LLD	Number of peaks	1.44	0.81	-0.41	0.17	0.15	Moderate
Effective Mass	LRA	Phase Start	Pre*	Pre/1*	0.61	0.37	0.35	Large
	LRA	Peak	0.30	0.18	-0.38	0.15	0.12	Moderate
		Key Determinates						

LRF	Number of peaks	1.51	0.59	0.47	0.22	0.20	Moderate
LRF	Time to peak	0.20	0.04	0.33	0.11	0.09	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics.

No commonalities were found between any of the key determinants and the impact kinetics of the cross. Unlike the GRF results, key determinants were identified for effective mass in the cross.

Table 25. Muscle activation determinates of impact kinetics in the LHH punch.

Muscle Group		Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	LRF	Peak	0.52	0.29	0.41	0.17	0.15	Moderate
	RLD	Time to Peak	0.32	0.15	-0.45	0.20	0.18	Moderate
	RTB	Phase Start	2*	Pre/3*	0.39	0.32	0.006	Trivial

	Key Determinates							
	RRA	Peak	0.31	0.17	0.54	0.29	0.27	Large
	LRF	Phase Peak	3*	Pre/Post*	0.38	0.14	0.12	Moderate
Fmax	RRA	Phase Start	2*	1/3*	0.40	0.16	0.14	Moderate
	RRA	Peak	0.31	0.17	0.34	0.12	0.09	Moderate
	LRF	Time to Peak	0.18	0.07	0.40	0.16	0.14	Moderate
	RLD	Time to Peak	0.32	0.15	-0.38	0.14	0.12	Moderate
	LLD	Duration	0.65	0.29	0.31	0.10	0.08	Small
	RTB	Phase End	Post*	3/Post*	0.34	0.02	0.01	Trivial
	LTB	Phase Start	1*	Pre/2*	-0.32	0.10	0.08	Small
	Key Determinates							
	LRF	Peak	0.52	0.29	0.60	0.36	0.34	Large
	RTB	Phase Start	2*	Pre/3*	-0.44	0.20	0.17	Moderate
Fmean	RRA	Phase Start	2*	1/3*	0.33	0.11	0.08	Small
	RRA	Peak	0.31	0.17	0.30	0.09	0.07	Small
	LRA	Phase Start	2*	1/3*	0.30	0.09	0.06	Small
	LRF	Time to Peak	0.17	0.05	0.51	0.26	0.24	Moderate
	RLD	Time to Peak	0.32	0.15	-0.43	0.19	0.16	Moderate
	Key Determinates							
	RTB	Phase Start	2*	Pre/3*	-0.55	0.31	0.29	Large
	RTB	Phase Peak	3*	2/Post*	0.40	0.16	0.13	Moderate

In the LHH, the RTB phase of activation start was negatively correlated to Fmax and Fmean (r = -0.44 and r = -0.55 respectively). RTB has a moderate magnitude inference with Fmax ($\bar{R}^2$ = 0.17) and a large magnitude inference with Fmean ($\bar{R}^2$ = 0.29). The RTB phase of peak activation was also positively correlated (r = 0.40) with Fmean ($\bar{R}^2$ = 0.13 and a moderate inference).

Table 26. Muscle activation determinates of impact kinetics in the RHH punch.

Muscle Group		Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	RRF	Number of Peaks	1.35	0.57	-0.38	0.14	0.12	Moderate
	RLD	Time to Peak	0.29	0.12	-0.43	0.18	0.16	Moderate
	LLD	Time to Peak	0.26	0.12	-0.5	0.25	0.24	Moderate
	RTB	Phase End	Post*	2/Post*	-0.65	0.42	0.40	Large
	LTB	Number of Peaks	1.30	0.64	0.32	0.10	0.08	Small
		Key Determinates						
	RTB	Peak	0.49	0.33	-0.57	0.32	0.31	Large
	LTB	Peak	1.01	1.23	-0.55	0.31	0.29	Large
Fmax	LRA	Phase Start	2*	1/2*	0.32	0.10	0.07	Small
	LRA	Phase Peak	3*	2/Post*	0.32	0.10	0.07	Small
	RRF	Number of Peaks	1.35	0.57	-0.41	0.17	0.15	Moderate
	LRF	Peak	0.82	0.49	0.35	0.12	0.11	Moderate
	RLD	Phase Peak	Post*	2/Post*	0.33	0.11	0.09	Moderate
	LLD	Phase Start	1*	Pre/3*	0.32	0.10	0.08	Small
	RTB	Phase End	Post*	2/Post*	-0.53	0.28	0.27	Large
	RTB	Peak	0.49	0.33	-0.39	0.15	0.13	Moderate
		Key Determinates						
	LLD	Time to Peak	0.26	0.12	-0.53	0.28	0.27	Large
	LTB	Peak	1.01	1.23	-0.54	0.29	0.28	Large
Fmean	LRA	Phase End	Post*	3/Post*	0.34	0.12	0.09	Moderate
	RRF	Number of Peaks	1.35	0.57	-0.40	0.16	0.14	Moderate
	RRF	Peak	0.50	0.4	-0.37	0.14	0.12	Moderate
	LRF	Peak	0.82	0.49	0.52	0.27	0.26	Large
	RLD	Phase Peak	Post*	2/Post*	0.44	0.19	0.17	Moderate
	RTB	Peak	0.49	0.33	-0.36	0.13	0.11	Moderate

RTB	Number of Peaks	1.30	0.46	0.35	0.12	0.10	Moderate
LTB	Peak	1.01	1.23	-0.31	0.09	0.07	Small
	Key Determinates						
LLD	Time to Peak	0.26	0.12	-0.40	0.16	0.14	Moderate
LRF	Time to Peak	0.20	0.07	0.47	0.22	0.20	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics.

Inversely from the results of the LHH, the RHH results found multiple impact kinetics negatively correlated to LTB peak activation. Impulse had an r value of -0.55 and Fmax had an r value of -0.54. Both key determinants had large magnitude relationships (impulse – $\overline{R}^2$ = 0.29 and Fmax – $\overline{R}^2$ = 0.28).

Combined Results

Taking the key determinants from the GRF and EMG results the final hierarchical regression was produced for the combined determinants of the impact kinetics. Combined findings for each punch type are presented in Tables 27 through 30. The tables contain determinants of impact kinetics ($\bar{R}^2$ and magnitude based inferences) and descriptive statistics (mean and standard deviation, median and min/max quantiles [when appropriate for the variable], r, and r^2) for all variables deemed relevant by the analysis.

Table 27. Combined determinates of impact kinetics in the jab punch.

	Muscle Group/Phase	Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	2	GRFDneg Rear Leg Z Axis	606.34	580.52	-0.49	0.24	0.22	Moderate
	LTB	Number of Peaks	1.30	0.55	0.45	0.20	0.19	Moderate
		Key Determinates						
	LLD	Phase Start	1*	Pre/Post*	0.63	0.40	0.38	Large
	1	Min Rear Leg Z Axis	-1492.62	354.26	0.61	0.37	0.36	Large
Fmax	3	Min Rear Leg Y Axis	-7.89	30.89	-0.59	0.35	0.34	Large
	LRF	Phase Start	1*	Pre/2*	-0.32	0.10	0.08	Small
		Key Determinates						
	LLD	Phase Start	1*	Pre/Post*	0.61	0.37	0.35	Large
	3	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.60	0.36	0.34	Large
Fmean	LTB	Number of Peaks	1.30	0.55	0.50	0.25	0.23	Moderate
	RTB	Duration	0.41	0.12	-0.48	0.23	0.22	Moderate
		Key Determinates						
	3	Min Rear Leg Y Axis	-7.89	30.89	-0.54	0.29	0.28	Large
	3	GRFDpos Rear Leg Z Axis	15671.32	4048.16	-0.52	0.27	0.26	Large
Effective Mass	2	GRFDpos Lead Leg Y Axis	1608.80	1317.64	-0.41	0.17	0.15	Moderate
	RTB	Phase Start	1*	Pre/2*	0.41	0.17	0.15	Moderate

	Key Determinates						
RTB	Duration	0.41	0.12	-0.51	0.26	0.24	Moderate
3	Min Lead Leg X Axis	31.14	67.53	- 0.48	0.23	0.21	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics. Phases are identified as follows: 1 = initiation, 2 = execution, and 3 = impact

Final results from the analysis of the jab found that except for Fmean, which had only GRF variables as key determinants, the other impact kinetic variables had one GRF and on EMG as key determinants. The LLD was the common variable across much of impact kinetics (3 out of 4 dependent variables) and had moderate to large inferences.

Table 28. Combined determinates of impact kinetics in the

	Muscle Group/Phase	Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	RLD	Duration	0.46	0.17	-0.65	0.42	0.41	Large
	LRF	Number of peaks	1.51	0.59	0.5	0.25	0.24	Moderate
		Key Determinates						
	3	Max Lead Leg Z Axis	-417.44	237.7	0.88	0.77	0.77	Very Large
	2	GRFDneg Lead Leg Z Axis	657.1	3286.22	0.64	0.51	0.50	Very Large
Fmax	3	GRFDneg Lead Leg Z Axis	-6689.09	8153.62	0.63	0.40	0.39	Large
	1	Min Lead Leg Z Axis	-908.29	210.32	0.64	0.26	0.24	Moderate
		Key Determinates						
	RLD	Phase Start	1*	Pre/2*	0.69	0.48	0.47	Large
	LTB	Duration	0.43	0.21	0.64	0.41	0.40	Large
Fmean	LRA	Phase Start	Pre*	Pre/1*	0.57	0.32	0.30	Large
	LLD	Number of peaks	1.44	0.81	-0.41	0.17	0.15	Moderate
		Key Determinates						

	3	Max Lead Leg Z Axis	-417.44	237.7	0.72	0.52	0.51	Very Large
	3	GRFDneg Lead Leg Z Axis	-6689.09	8153.62	0.67	0.44	0.43	Large
Effective Mass	LRF	Number of peaks	1.51	0.59	0.47	0.22	0.20	Moderate
	LRF	Time to peak	0.20	0.04	0.33	0.11	0.09	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics. Phases are identified as follows: 1 = initiation, 2 = execution, and 3 = impact

Unlike the jab, results from the cross were separated into only GRF (impulse and Fmean) or EMG (Fmax and effective mass) when determining impact kinetics. Impulse and Fmean had a common determinate in vertical GRFDneg of the lead leg. Z axis GRFDneg in the lead leg had positive correlations (impulse – r = 0.64 and Fmean – r = 0.67) and large to very large magnitude relationships (impulse – $\bar{R}^2$ = 0.50 and Fmean – $\bar{R}^2$ = 0.43) with the impact variables of note. These relationships were found in different phases, with the impulse determinant occurring in the execution phase and the Fmean determinant occurring in the impact phase.

Table 29. Combined determinates of impact kinetics in the LHH punch.

	Muscle Group/Phase	Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	2	Min Rear Leg Z Axis	-606.22	295.91	0.42	0.18	0.16	Moderate
	LRF	Phase Peak	3*	Pre/Post*	0.38	0.14	0.12	Moderate
		Key Determinates						
	RRA	Peak	0.31	0.17	0.54	0.29	0.27	Large
	3	Min Rear Leg X Axis	-150.22	85.51	0.43	0.18	0.16	Moderate
Fmax	3	Min Rear Leg X Axis	150.22	85.51	0.45	0.20	0.18	Moderate
	RTB	Phase Start	2*	Pre/3*	-0.44	0.20	0.17	Moderate
		Key Determinates						
	LRF	Peak	0.52	0.29	0.60	0.36	0.34	Large

	3	GRFDneg Rear Leg X Axis	-530.12	847.2	-0.54	0.29	0.28	Large
Fmean	4	Max Rear Leg Y Axis	21.8	46.27	0.46	0.21	0.19	Moderate
	RTB	Phase Peak	3*	2/Post*	0.40	0.16	0.13	Moderate
		Key Determinates						
	RTB	Phase Start	2*	Pre/3*	-0.55	0.31	0.29	Large
	3	GRFDneg Rear Leg X Axis	-824.45	1444.8	-0.50	0.25	0.23	Moderate

* indicates that median and min/max quantiles were used as descriptive statistics. Phases are identified as follows: 1 = wind-up, 2 = initiation, 3 = execution, and 4

LHH results were evenly split with key determinants coming both from GRF and EMG findings for all impact kinetics. During the execution phase, X axis GRFDneg of the rear leg had a negative correlation with Fmax (r = -0.54) and Fmean (r = -0.50). These commonalities had moderate to large inferences (Fmax – $\bar{R}^2$ = 0.28 and Fmean – $\bar{R}^2$ = 0.23).

Table 30. Combined determinates of impact kinetics in the RHH punch.

	Muscle Group/Phase	Variable	Mean/Median	SD/Quantiles	r	r^2	$\bar{R}^2$	Inference
Impulse	LTB	Peak	1.01	1.23	-0.55	0.31	0.29	Large
	1	Max Rear Leg Z Axis	-473.76	101.66	0.47	0.22	0.20	Moderate
		Key Determinates						
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	-0.69	0.48	0.47	Large
	RTB	Peak	0.49	0.33	-0.57	0.32	0.31	Large
Fmax	LLD	Time to Peak	0.26	0.12	-0.53	0.28	0.27	Large
	1	Max Rear Leg Z Axis	-473.76	101.66	0.53	0.28	0.26	Large
		Key Determinates						
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	0.62	0.38	0.37	Large
	LTB	Peak	1.01	1.23	-0.54	0.29	0.28	Large
Fmean	LRF	Time to Peak	0.20	0.07	0.47	0.22	0.20	Moderate
	LLD	Time to Peak	0.26	0.12	-0.40	0.16	0.14	Moderate
		Key Determinates						
	1	Max Rear Leg Z Axis	-473.76	101.66	0.68	0.46	0.45	Large
	4	GRFDneg Lead Leg X Axis	-1678.41	1563.44	-0.67	0.45	0.44	Large

* indicates that median and min/max quantiles were used as descriptive statistics. Phases are identified as follows: 1 = wind-up, 2 = initiation, 3 = execution, and 4 = impact

The final determinants of the RHH had one commonality between impact kinetics, GRFDneg of the lead leg in the X axis during the impact phase. The GRFDneg variable had a positive correlation to Fmax (r = 0.62) and a negative correlation to impulse (r = -0.69) and Fmean (r = -0.67). The relationship of lead leg GRFDneg in the X axis to the impact variables had a large magnitude in all cases (impulse – $\overline{R}^2$ = 0.47, Fmax – $\overline{R}^2$ = 0.37, and Fmean – $\overline{R}^2$ = 0.44).

Discussion

Using the proposed determinants of impact kinetics, lower body contribution and muscle activation patterns, it was possible to develop a far greater understanding of straight and hook punches in boxers. Direct measurement of GRF and EMG combined with key impact kinetics, all collected in situ, have confirmed much of the theoretical and causal links in the literature (Lenetsky et al., 2013; Lenetsky et al., 2015; McGill et al., 2010). That is, this paper is the confirmation that the lower body's contribution and muscle activation patterns do play a major role in punching impact kinetics. Analysis of these contributors within the structure of the recently developed phases of punching further focused the results, producing insight into specific kinematic events and providing insight for practitioners and researches alike. The determinant findings have expanded the understanding of punching through an approach exploring the concepts in a discriminate manor, reducing the numerous variables to only those deemed paramount for performance. Based on the findings, it can be deduced that there is no one key determinant of impact kinetics in punching. Although, the importance of the lower body stands out in the results over that of muscle activation patterns of the upper body musculature. The results also highlight the uniqueness of each punch type. Each type can be considered its own specific skill within boxing, with varied demands and individual keys to performance. Similarly, the uniqueness of the impact kinetics themselves attract attention, as such, this section will be divided by each kinetic variable, and then focused by punch type.

Impulse

Jab

The key GRF determinants of the jab were minimal Z axis loading of the rear leg during the initiation phase and GRFDneg in the rear leg during the execution phase. The rear leg in the initiation phase was characterised by lower Z axis values early in the phase before a steep increase in loading as the phase ends. These findings indicate that the greater the decrease in loading of the rear leg early in the initiation phase the larger the impulse during impact (r = 0.61). In the execution phase, Z axis GRFDneg of the rear leg negatively affected impulse (r = -0.49). A rear leg decrease in Z axis loading has been found in the execution phase previously (Lenetsky, Brughelli, et al., 2017). This new finding adds context to the deloading, showing that while a fundamental part of the phase, if produced too aggressively it may reduce impulse.

EMG key determinants both positively influence impulse in the jab. The phase of activation starts in the LLD (initiation phase) had a large magnitude relationship with impulse (r = 0.63). It is unlikely the that this LLD activation was used to aid in the rotation of torso (due to ipsilateral factors), instead it is likely activated antagonistically in response to shoulder flexion occur during the phase producing stability at the shoulder. The number of peaks performed by the LTB positively correlated (r = 0.45) with impulse. With a mean greater than a single peak (1.3) it is likely that the multiple peaks theorized in previous research (McGill et al., 2010) do positively improve impulse in the jab. Although, the lack of a clear DPMA does raise questions into the necessity of two distinct individual peaks for punching performance. Final combined key determinants for impulse when performing the jab (LLD phase start and minimal Z axis loading during initiation phase) highlight the mixed nature of the key determinants and in this case the greater importance of muscle activation patterns over GRF.

Cross

Impulse related GRF results from the cross highlight the importance of loading the lead leg during later phases of the punch. Maximal Z axis loading of the lead foot during the impact phase was positively correlated (r = 0.88) with impulse. Analysis of the GRF pattern (Lenetsky, Brughelli, et al., 2017) previously performed found a stable, relatively unchanged Z axis loading throughout the phase, that according to these findings should be high. Z axis GRFDneg of the lead leg during the execution was also positively correlated to impulse (r = 0.64). After a large loading in the initiation phase, usually coinciding with the end of a lead leg step forward, loading decreased in the lead leg as weight distribution was spread slightly to the rear leg. These findings together are indicative of a quick but moderate deload of the lead leg during the execution phase and maintained lead leg force during impact being key to improved jab impulse.

RLD duration of activity results were negatively correlated (r = -0.65) with impulse in the cross. The RLD activation is probably utilized in a similar manner to the proposed LLD activation in the jab, to stabilize the shoulder joint during the action and impact. The negative correlation to the duration of activation could be due to the extended activation time reducing the LLD's ability to rotate the torso, antagonistic resistance. It could also be a result of the higher time of force production reducing the velocity due to the force-velocity relationship (Bartlett, 2007). Key determinants of impulse in the cross were composed solely of the GRF variables.

LHH

Impulse produced by the LHH was determined by minimal X axis loading of the rear leg during the execution phase and minimal rear leg Z axis loading during the initiation phase. Minimal X axis loading (negative findings from the rear leg equate to force applied towards the mid-line of the boxer) was likely a force used to stabilize the body during the high velocity rotation of the hook and prepares the boxer for a bi-lateral decrease in lower limb Z axis loading seen before the start of the impact phase. The wind-up phase of the LHH started as the boxer loads their lead leg substantially greater than the rear. This load distribution continues throughout the movement, but was most important during the initiation phase, where minimal rear leg loading of the Z axis positively influenced (r = 0.42) impulse. If a boxer fails to load the lead leg (deload the rear leg) the LHH would produce sub-optimal impulse as they could not rotate across the body.

EMG key determinants for LHH when producing impulse were the peak activation of the RRA and the phase of peak activation of the LRF. RRA peak activation would aid in rotation of the torso during the initiation and execution phases. Greater activation should produce increase in torso rotation velocity and thus impulse (Bartlett, 2007). It is interesting that a lower body related variable, the peak activation of the LRF in the execution phase, is another key determinant of impulse. The timing of activation to produce a jump or bi-lateral Z-axis deloading was more important than all other muscle activation patterns apart from the RRA peak. The combined key determinates of minimal X axis GRF and RRA activation serve to highlight the rotational aspect of the LHH, similar findings were not found in the more linear straight punches when determining impulse.

RHH

GRF determinants of impulse in the RHH were GRFDneg of the lead (X axis) during impact and maximal rear leg loading of the Z axis during the wind-up phase. During the impact of the RHH the current literature theorizes that a reduction of compliance would improve impact kinetics (Lee & McGill, 2016). A GRFDneg (loading or force applied away from the mid-line) would cause compliance in the boxer, producing an energy leakage (McGill, 2014), and reducing impulse ($r = -0.69$). In a mirroring action to the LHH, the wind-up phase is started as weight is shifted to the rear leg in preparation for the rotation later in the punch. The loading of the rear leg (Z axis) during the wind-up phase positively correlates ($r = 0.47$) with impulse. The higher the loading of the rear leg the greater the impulse, as this may allow the boxer to transfer more weight back towards the lead leg later in the punch and rotate with greater force.

Key determinants found from the EMG results were both negatively correlated with impulse and were both found in the upper body (RTB and LTB peak). This is potentially due to excess tension during the punch slowing the movement through the same force-velocity relationship covered above. According to current theories there should be contraction in the triceps to stiffen the arm on impact (Neto & Magini, 2008; VencesBrito et al., 2011), and triceps activity extending the contralateral arm at the shoulder could also help with rotation by adding momentum to the movement. These negative findings do not discount these theories on the role of the triceps in punching, instead serve to add a warning that overactive triceps activity can reduce impulse during impact. The combined final determinants (X axis GRFDneg and RTB peak activation) reinforce the concept that the upper body should be relatively relaxed during the movement and the lower body must be active to support the body during impact. A novel and previously undeveloped concept in the literature.

Fmax

Jab

Fmax produced by the jab was determined by the GRF variables GRFDpos of the rear leg (Z axis in the impact phase) and minimal rear leg loading of the Y axis (impact phase). During the execution phase of the jab there was a large deload of rear leg as the lead leg accepts the majority of the body weight. Upon impact of the fist, the quicker the body weight was loaded on the Z axis of the rear leg the greater the Fmax. This would serve to buttress the body against the impact (reducing compliance) and improve Fmax. Minimal loading of the Y axis (negative values are force applied away from the target) negatively correlated with Fmax ($r = -0.49$). A force applied away from the target would serve as a braking force, reducing forward momentum. A force applied away from the target could serve to "block" (Morriss & Bartlett, 1996; Morriss et al., 2001) the rear leg to increase rotation, but from the findings it appears that it is not beneficial in this case and that forward momentum was the key to Fmax in jab.

Key determinants derived from EMG results were the phase of activation start of the LLD and LRF. Like findings of jab contributors to impulse, LLD activation in the initiation phase had a large positive relationship with Fmax. This early activation was likely not used for torso rotation as rotation has not found during the initiation phase (Lenetsky, Brughelli, et al., 2017). Instead, it is probably used to stabilize the shoulder as it flexes during the phase. LRF activation start was negatively correlated ($r = -0.32$) with Fmax. This potentially could be due to an early activation occurring before the step was initiated. A later activation, coinciding with the step, could be a more efficient pattern increasing Fmax. LLD phase of activation start and rear leg Z axis GRFDpos during the impact phase were the key combine determinants of jab Fmax. This finding reinforces the importance of the LLD in the jab and the over importance of bracing the body for optimal force transfer. In this case the LLD to brace the shoulder and GRFDpos to brace the low body.

Cross

The primary GRF determinant of Fmax in the cross was the GRFDneg of the lead leg (Z axis) during the impact phase (large magnitude). This rapid unloading of the lead leg in the Z axis is paramount to Fmax production due to a change in force vector that occurs during the impact (Lenetsky, Brughelli, et al., 2017). Greater Y and X axis loading occur at the lead leg during the phase to potentially direct force into the target. Minimal loading of the lead leg (Y axis) was the second key determinant of Fmax production in the cross ($r = -0.49$). This is expected due to previous findings that show a rear leg drive towards the target is a crucial component of the cross (Lenetsky, Brughelli, et al., 2017). Overactive loading of the lead leg would put boxers at a disadvantage in producing the forward drive, producing braking force and reducing that drive forward.

EMG determinants RLD phase of activation start and LTB duration of activation were both positively correlated with Fmax ($r = 0.69$ and $r = 0.64$ respectively). Initiation phase activation of the RLD was comparable to the LLD activation start during the jab. In the same way, the LLD activation was likely used for shoulder stabilization, the RLD activation (ipsilateral to the punching arm) was thought to be a bracing contraction. LTB duration of activation occurs due to the extension of the arm in the initiation phase often performed by boxers (Lenetsky, Brughelli, et al., 2017). This potentially aids in the production of Fmax as after the extension in the initiation phase the arm was retracted to the torso in an action to add angular momentum to the torso rotation performed in later phases. Contrary to the combined key determinants of impulse, the final determinants of Fmax production were only EMG variables. This may shed light on the differences in impulse and Fmax, impulse appears to be influenced by greater application of force produced by the lower body, while Fmax may be influenced by variables that increase angular velocity of the torso. A slower penetrative punch would have higher impulse, and a quicker snapping punch produces high Fmax.

LHH

LHH Fmax was determined by the GRF variables of GRFDneg and minimal force, both in the rear leg, in the X axis, and during the execution phase. X axis GRFDneg had a negative correlation ($r = -0.59$), while minimal X axis force had a positive correlation with Fmax (r = 0.45). During the execution phase, the rear leg was characterized by a decreased force (force applied towards the boxer's mid-line) at the beginning of the phase, carried over from the loading which occurs in the initiation phase. As the phase continued, the rear leg deloaded in the X axis before the impact phase began. With the findings from this study, it is indicated that optimal Fmax in the LHH is produced by force applied toward the mid-line early that does not continue to increase throughout the phase.

Peak activation of the LRF and the phase of activation start of the RTB (initiation phase) were the key EMG determinants of Fmax in the LHH. LRF peak activation positively correlated with Fmax (r = 0.60), indicative of the importance of the lead leg's ability to activate and drive towards the target. Like the findings of the RHH determinants of impulse, the EMG variable the non-punching arm, RTB in this case, was negatively correlated (r = -0.44) with Fmax. Unlike the RHH impulse findings, the LHH Fmax result was not peak activation, instead was activation start. Although, it is possible that the underlying mechanism is the same. That is, the fact that RTB reached a point where the analysis identified an activation means that there was potentially velocity dampening stiffness in the upper body. A potential factor in this is that a failure to properly position the rear arm in a defensive position in the wind-up phase may require activation during the initiation phase to properly protect the fighter as the punch is thrown. The combined key determinants of Fmax in the LHH were the GRFDneg of the rear leg in the X axis, and the peak activation of the LRF. Combined, these results display the importance of the lower body in the LLH, either to reduce impact kinetics or improve them.

RHH

Both GRF determinants of the RHH were positively correlated to Fmax. Lead leg GRFDneg in the X axis during impact (r = 0.62) contributed to Fmax as the force vector changes during the impact phase with increased force application occurring towards the target (positive Y axis force) (Lenetsky, Brughelli, et al., 2017). If a quick decrease in the forces applied towards the mid-line of the boxer did not occur, it appears that the force vector would not be optimised at impact for Fmax production. The wind-up phase of the RHH begins as the boxer's weight shifts to the rear leg in preparation for the punch. This loading in the Z axis was a key determinant (r = 0.53) in the production of Fmax. It was apparent that the pre-loading of the rear leg was paramount before force was applied in the X and Y axis during the initiation phase to propel the boxer and boxer's fist towards the target.

The EMG determinants of Fmax were both upper body variables (LLD and LTB) and were both negatively correlated to Fmax. LLD time to peak activation ($r = -0.53$) negatively affected Fmax likely due to an overaction on LLD activity. The LLD is used in the RHH to rotate the torso, bringing the rear arm around into contact. Findings indicate that a sustained activation taking longer periods of time to reach the peak is a sub-optimal pattern. Similarly, LTB peak activation ($r = -0.53$) negatively influenced Fmax. This common theme of negative relationships with activation in the upper body reinforces the concept that a relaxed, low activation in the upper body is a key to effective punching. Additionally, the final key determinants of Fmax in the RHH were the GRF variables, another common theme seen across punch types. The contribution of the lower body is potentially the key variable in punching performance.

Fmean

Jab

GRF determinants of the jab both had negative relationships with Fmean during the impact phase. Minimal rear leg force in the Y axis (force applied away from the target) reduced Fmean ($r = -0.54$), probably due to a failure to remain rigid during the impact. A consistent (relatively low) force applied towards the target appears necessary to properly produce Fmean, an action previously thought only to be required for improved effective mass (Lenetsky et al., 2015). GRFDpos in the Z axis of the rear leg also negatively affected ($r = -0.52$) Fmean. This is again an indicator that the rear leg must maintain some forward force application during impact and that loading in the Z axis would be due to a failure to maintain that posture, forcing the boxer back on to their rear leg.

Jab determinants derived from EMG were upper body variables once again. The number of activation peaks in the LTB during the jab had a positive relationship with Fmean ($r = 0.50$). A mean of 1.3 peaks was found in the LTB during the jab, like the determinants of impulse, this multiple peak finding agrees in part with the findings of VencesBrito et al. (2011), multiple muscle activation peaks improve impact kinetics. Although, this finding places greater importance of multiple peaks in the attacking limb over the role of the core musculature, which has been argued to be key in previous literature (Lee & McGill, 2016; McGill et al., 2010). The second EMG determinant of the jab, RTB duration of activation, had a negative relationship (r = -0.48) with Fmean. These results again follow the pattern that excess activation of the upper body, in this case activation duration, produces sub-optimal impact kinetic results. Results from the combined final hierarchically were all once again lower body specific.

Cross

Fmean GRF determinants of the cross were Z axis variables, both occurring during the impact phase. The cross punch was characterized by a weight shift from the rear leg to the lead in the Z axis during the initiation phase. After which, the lead leg propelled the boxer forward in the Y axis during the execution phase (Lenetsky, Brughelli, et al., 2017). Maximal Z axis force in the lead leg had a strong relationship with Fmean results (r = 0.72). Greater Z axis loading of the lead leg may be needed to produce the forward drive observed during the early portions of the impact phase in which Y axis force was still increasing towards the peak (Lenetsky, Brughelli, et al., 2017). The second GRF determinant was interestingly the lead leg GRFDneg in the Z axis (r = 0.67), potentially the opposite of the first determinant. It is probable that maximal Z axis loading was key for the early portion of the impact phase, which then quickly deloaded as the impact phase continues, due to a change in force vector as the Y axis drive increased towards the end of impact.

The Fmean produced by the cross was determined by the EMG variables LRA phase of activation start (activating before the initiation phase) and the number of peaks produced by the LLD (mean of 1.44 peaks). LRA activation start was positively correlated to Fmean (r = 0.57), and LLD number of peaks was negatively correlated (r = -0.41). The phase of activation start in the LRA could be a pre-activation before the LRA was used to aid in the rotation found in the initiation phase. This is one of the few key determinants found in this study that was produced by the LRA or RRA. Traditional boxing training places a major focus on training of the rectus abdominis (Dempsey, 1950), these results are indicative that this may be misused training focus. The negative relationship found with the number of peaks in LLD activation, stands in stark opposition to the current literature (Lee & McGill, 2016; McGill et al., 2010). One would expect to find a positive relationship with multiple peaks as explained by the theories related to DPMA. These results could call into question the effectiveness of DPMA in general, or more likely could narrow the importance of DPMA to more specific muscle groups. It can be deduced from the hierarchical regression that multiple activations are beneficial when occurring in the triceps of punching arms, but may be harmful when occurring in the latissimus dorsi. LLD activation during the cross was clearly utilized as part of torso rotation, but over activity, much like found in the other punch types, can reduce the velocity of the torso rotation. Final determinants of Fmean in the cross were yet again GRF variables.

LHH

Primary GRF determinants of the Fmean in the LHH were both rear leg variables, GRFDneg in the X axis during the execution phase and maximal Y axis force during impact. During the ending of the execution phase, there was a decrease in X axis force applied by the rear leg towards the mid-line of the boxer. This appears as a positive shift in the GRF moving towards a zero point. Like the findings of the Fmax determinants, X axis GRFDneg of rear leg had a negative relationship with Fmean ($r = -0.50$) indicating that if the latter portions of the phase did not have a decrease in force (a positive signal) towards the mid-line Fmean would not be optimised. Impact during the LHH was characterised by an increase in rear leg contribution towards the target in the Y axis. This was a key determinant of Fmean ($r = 0.46$), applying continued force into the target during the impact.

Both EMG determinants of the LHH were found to be RTB related variables, phase of activation start ($r = -0.55$) negatively affecting and phase of activation peak ($r = 0.40$) positively affecting Fmean. These apparently contradictory results found in RTB activation patterns shed light into the role of the non-punching arm in the LHH. The triceps appear to be used in shoulder extension to aid in the rotation of the torso, but if the activation is of too long of a time (starting in the initiation phase) then it could be indicative of upper body stiffness, a topic covered frequently above. Instead, a quick activation appears to be the best strategy to aid in rotation without reducing velocity. The final determinants of Fmean in the LHH were the phase of activation start and the X axis GRFDneg. This echoes the theme found repeatedly in impact kinetic determinants, a failure to maintain a relaxed upper body reduces velocity of impact (and thus impact force) and that properly applied forces from the lower body are required to maximize impact forces.

RHH

Key GRF determinants of Fmean in the RHH were lead leg GRFDneg in the X axis during impact and maximal Z axis forces in the rear leg during the wind-up phase, both variables had positive relationships (r = 0.45 and 0.46 respectively). These are the same variables as those found in the impulse and Fmax determinants. Although, Fmax had a negative correlation with GRFDneg, impulse and Fmean had positive correlation. These findings display the differences between the optimisation of impulse and Fmean and Fmax. That is, methods to reduce the boxer's compliance appear to be necessary to increase the time of impact (increasing impulse and Fmean), while quicker application of force into the target is likely needed for Fmax. Across all the above impact kinetics of the RHH, maximal loading of the rear leg in the Z during the wind-up phase was positively associated with impact kinetics. It is clear that without loading of the rear leg to propel the boxer forward, the RHH will not reach its potential at impact.

Time to peak activation of both the LLD and the LRF were the key EMG determinants of Fmean in the RHH. Again, LLD activation patterns were negatively associated with an impact kinetic (r = -0.40) and again it is likely that this result was an outcome of overactivation of the LLD causing a reduction of torso rotation velocity. LRF time to peak activation had a positive relationship (r = 0.47) with Fmean, as it is probable that without force applied over an extended period of time throughout the strike, the wind-up phase weight shift to the rear leg would not occur, nor the drive forward and transversely found in the execution and impact phases (Lenetsky, Brughelli, et al., 2017). Final key determinants were the GRF variables as found so often in the other punch types.

Effective Mass

Jab

Effective mass was determined by the GRF variables of minimal lead leg force in the X axis during the impact phase and GRFDpos in the lead leg (Y axis) during the execution phase of the jab. Both variables had negative relationships with effective mass. Minimal X axis force was negatively correlated to effective mass (r = -0.48), because during the impact phase, boxers utilizes the lead leg to apply force towards the mid-line (a positive GRF result). The lower this force, or even potentially force applied away from the mid-line, the less aligned the lead attacking arm would be. This would result in sub-optimal joint alignment at the wrist, elbow, and, shoulder, which could produce compliance and reduce effective mass (Lenetsky et al., 2015). Additionally, without a force applied towards the mid-line, it is possible that the impact of the jab could force the lead arm posteriorly, moving down the kinetic chain and forcing the lead side of the hip posteriorly. Mid-line force application would aid in stabilising the hip and potentially the shoulder. The negative relationship between Y axis GRFDpos in the lead leg and effective mass (r = -0.41), is likely due the importance of a decrease in Y force (braking forces) found in the profile of the jab (Lenetsky, Brughelli, et al., 2017). This braking force could be used as block, a movement found often in rotational throwing sports (Morriss & Bartlett, 1996; Morriss et al., 2001), securing the pelvis to allow for greater rotation at the torso throughout the impact phase.

Activation patterns of the RTB were both final EMG determinants of effective mass in the jab. RTB duration of activation had a negative relationship (r = -0.51) and the phase of activation start (initiation phase) has a positive relationship (r = 0.41) with effective mass. As found repeatedly throughout the development of the determinants of other impact kinetics, these findings display the importance of the non-punching arm. In this case the arm extends during the initiation phase and then withdrawing later to aid in rotation. These findings also highlight the negative effects of over activation of the musculature in the upper body. The final key determinants of effective mass in the jab were lead leg GRFDpos in the Y axis and the phase of activation start of the RTB. These findings are in contrast to those currently theorized in the literature for methods to optimize effective mass (Lenetsky et al., 2015). Instead of DPMA being a primary determinant of effective mass, two variables theorized to optimize the rotation of the torso were paramount to the development of effective mass in the jab. Further exploration into the causation of effective mass is still needed, but these results call into question some of the current theories on the development of effective mass through DPMA (McGill et al., 2010), while potentially putting more emphasis on other theories on the continued application of force during impact (Lenetsky et al., 2015).

Cross

Surprisingly, no GRF determinants fit the criteria for inclusion as key determinants of effective mass in the cross. It is possible that GRF has no impact on effective mass, but that is doubtful in the light of the results found from the determinant analysis of the other impact kinetics, specifically the impulse results which are a key component of effective mass (Neto & Magini, 2008). A more likely explanation is a limitation in the collection of effective mass data. From the 2D analysis findings the jab is a linear punch, moving straight as it is thrown with little deviation mediolaterally. The cross was found to have substantial deviation mediolaterally when thrown maximally by the boxers in this cohort. Since the velocity analysis of the punch was performed only in 2 dimensions it was not possible to track velocity changes in the frontal plane and this could have resulted in inaccuracies in the per-impact velocity calculation. With these errors in pre-impact velocity the final effective mass measurement may be questionable. Although, these potentially questionable results did have moderate correlations with EMG determinants.

Two LRF variables were key determinants of effective mass in the cross, both with positive relationships. The number of peak activations (mean of 1.5 activations per punch) and time to peak activation potentially resulted in increased effective mass ($r = 0.47$ and 0.33 respectively). If accurate, the relationship to the number of peaks does match current theories relating to DPMA, and indicates that an activation, relaxation, activation pattern in the LRF does improve effective mass above all other contributors. LRF time to peak activation follows a similar pattern as found in other lower limb activations. An extended activation leading up to the peak allowing for the protracted forces required throughout the movement as found in the other impact kinetic determinants of the cross. The EMG determinants were also the final key determinants as no GRF variables fit inclusion criteria.

Combined final determinant results

The final key determinants taken from all punch types observed, establish straight and hook, rear and lead punches as movements in boxing that are unique to themselves, but similar in general concepts. Likewise, the impact kinetics examined have unique determinants within and across each punch type, but with specific similarities seen in Table 31.

	Variable Type	Variable	Muscle Group/Phase	Location	Inference
Key Determinants of the jab					
Impulse	EMG	Phase Start	LLD	Upper Body	Large (+)
	GRF	Min Rear Leg Z Axis	1	Lower Body	Large (+)
Fmax	EMG	Phase of Start	LLD	Upper Body	Large (+)
	GRF	GRFDpos Rear Leg Z Axis	3	Lower Body	Large (-)
Fmean	GRF	Min Rear Leg Y Axis	3	Lower Body	Large (-)
	GRF	GRFDpos Rear Leg Y Axis	3	Lower Body	Large (-)
Effective Mass	EMG	Duration	RTB	Upper Body	Moderate (-)
	GRF	Min Lead Leg X Axis	3	Lower Body	Moderate (-)
Key Determinants of the cross					
Impulse	GRF	Max Lead Leg Z Axis	3	Lower Body	Very Large (+)
	GRF	GRFDneg Lead Leg Z Axis	2	Lower Body	Very Large (+)
Fmax	EMG	Phase Start	RLD	Upper Body	Large (+)
	EMG	Duration	LTB	Upper Body	Large (+)
Fmean	GRF	Max Lead Leg Z Axis	3	Lower Body	Very Large (+)
	GRF	GRFDneg Lead Leg Z Axis	3	Lower Body	Large (+)
Effective Mass	EMG	Number of Peaks	LRF	Lower Body	Moderate (+)
	EMG	Time to Peak	LRF	Lower Body	Moderate (+)
Key Determinants of the LHH					
Impulse	EMG	Peak	RRA	Upper Body	Large (+)
	GRF	Min Rear Leg X Axis	3	Lower Body	Moderate (+)
Fmax	EMG	Peak	RTB	Lower Body	Large (+)
	GRF	GRFDneg Rear Leg X Axis	3	Upper Body	Large (-)
Fmean	EMG	Phase Start	RTB	Upper Body	Large (-)

	GRF	GRFDneg Rear Leg X Axis	3	Lower Body	Moderate (-)
		Key Determinants of the LHH			
Impulse	GRF	GRFDneg Lead Leg X Axis	4	Lower Body	Large (-)
	EMG	Peak	RTB	Upper Body	Large (-)
Fmax	GRF	GRFDneg Lead Leg X Axis	4	Lower Body	Large (+)
	EMG	Peak	LTB	Upper Body	Large (-)
Fmean	GRF	Max Rear Leg Z Axis	1	Lower Body	Large (+)
	GRF	GRFDneg Lead Leg X Axis	4	Lower Body	Large (-)

Table 31. Combined final determinates of impact kinetics in boxing punches.

Of the 28 final determinants of impact kinetics, more than half (16) were GRF determinants. Of the 12 final EMG determinants nine were upper body variables and three were lower body. These 19 lower body determinants, a clear majority of all determinants, confirm the theories of Lenetsky and colleagues (2015), that the lower body's contribution is key to punching performance. Furthermore, the majority of the GRF variables (10 out of 16) took place during the impact phase, further supporting the theories of Lenetsky and colleagues relating to force transfer (Lenetsky et al., 2015). These combined new findings add greatly to the current knowledge of punching in boxing. In contrast to established theories, only one of the final variables was specifically related to DPMA. Although, the only multi-activation variable was a final determinant of effective mass, which would be expected as outlined by previous research (McGill et al., 2010; VencesBrito et al., 2011). The other EMG final determinants, nine in total, were upper body related. Of these, four negatively affected impact kinetics and five were positively related. All four of the negative correlated EMG were in the triceps, whereas the positive correlations were primarily in the latissimus dorsi and rectus abdominis. These findings highlight the usage of the core musculature in punching and the necessity of relatively limited involvement of the arms in punching.

It is important to note that many upper body EMG determinants (specifically related to the latissimus dorsi) not included as final determinants were negatively correlated to impact kinetics. Demonstrating that while positively correlated as final determinants, if performed incorrectly, upper body musculature activations can reduce performance. Moreover, the final determinants indicate that optimal impact kinetics are produced by substantial contribution from the lower body to propel, rotate, and stabilise the boxer, while rotation is continued through the core musculature, judiciously activated, and the remainder of the upper body is relaxed to optimize the punch.

Conclusion

Using in situ measures of GRF, EMG, and impact kinetics monitoring the punches performed by competitive boxer, the key determinants of straight and hook were identified. This was achieved through multiple hierarchical regressions to find GRF and EMG determinants of impact kinetics. A final hierarchical regression combined the findings to identify the key determinants of impulse, Fmax, Fmean, and effective mass in the punches of boxers. The determinants establish the uniqueness of each punch type and of each impact variable, while providing a general frame work that appears to be universal in boxing punches. A frame work that places the lower body's contribution to impact kinetics as the paramount variable, with important contribution from the core musculature, and a necessity for the upper body to remain relaxed through the punching action. These findings agree with much of the current literature regarding punching, but deviate in several key areas primarily around the importance of DPMA. This work serves as a starting point for further longitudinal and interventional investigations, based around the novel quantifiable findings of this study and the theoretical works previously produced.

CHAPTER 9

Conclusion, direction of future research, and practical applications

Conclusion

The aim of this PhD thesis was to answer the question, "What determines effective punching in boxers?" That broad question was broken down into four primary aims:

1. Determine if effective mass in the context of the spring mass model is an accurate representation of impact kinetics in punching.
2. Ascertain the importance of ground reaction forces (GRF) in straight and hook punches in boxers.
3. Develop a phase model of straight and hook punches in boxers focused on GRF, muscle activation patterns, and kinematics.
4. Determine the role of muscle activation patterns and GRF in the production of effective mass, impulse, peak and mean force.

To answer the central question of the thesis, first the current literature exploring contributors to punching impact kinetics were explored (Chapter two). This review established the importance of GRF in punching (aim two). A second review was performed exploring effective mass in combat sports and its relationship to other commonly measured impact kinetics (Chapter three). Synthesis of the literature served to define effective mass in the context of combat sports and identified its importance as one of many key variables of impact. Although, potential limitations of the concept relating to the spring mass model were identified (aim one). To triangulate the findings from chapters two and three with expert knowledge, a group of boxing coaches were interviewed using thematic content analysis, a qualitative method (Chapter four). The expert boxing coaches unanimously agreed with Chapter two's findings in that the lower body's contribution was key to effective punching (aim two), but did not present any information relevant to effective mass. Section two of the thesis focused on methods of measuring impact kinetics in boxing (Chapters five and six). Chapter five established a valid and reliable lab test that used training specific equipment in a simple and affordable manner. Chapter six explored the newly developed method's practical reliability and variability through the testing of a cohort of inexperienced participants and trained boxers. The work of these chapters found that the method developed is valid, but had moderate reliability at best when testing human participants.

With a research based rationale and a method to measure impact kinetics, section three explored the aims of the thesis through experimental studies on a cohort of experienced boxers. Chapter seven defined that phases of straight and hook punches in boxers (aim three). This experimental chapter based the phases off GRF as indicated by the findings of Chapters two and four. Electromyography and high-speed video were used to expand on the GRF findings and elucidate the action of straight and hook punches. The results from the defined phases identified the uniqueness of each punch type and the differences found between the punches when thrown with the rear and lead hands. This result provided a framework for future research to share a common structure, a concept lacking in the literature. The study also identified a common trend among the punches, continued GRF application during the impact phase of the punch. This finding called into question the representation of effective mass through the spring mass model (aim one), as if GRF is applied during impact then the punch is not a ballistic impact. The final study of the thesis (Chapter eight), combined the concepts and theories developed throughout to establish determinants of impact kinetics in straight and hook punches (aim four). The analysis of the study used the phase model established in Chapter seven (aim three) and found that GRF was the primary determinant of impact kinetics (aim two). Further analysis determined that GRF application during the impact phase contributed as a major factor. This added evidence to the questioning of the spring mass model as a method of describing punching and explaining effective mass (aim one). In addition, results of upper body muscular activation patterns contradicted many of the current theories of the role of double peak muscle activation. This is due to the fact that the majority of the upper body key determinants were related to a generally relaxed state and not the contraction, relaxation, and contraction found in double peak muscular activation.

Throughout the process of researching for this PhD several key areas of interest were identified that potentially limit the impact of the findings produced. These areas of interest are specific to the methods of measurement utilized in the PhD. As explained in Chapter Six, the measurement of a single maximal punches does not necessarily reflect the context of punching in boxing, in which multiple punches are thrown in combination and with varying levels of intensity. This limitation is found throughout punching related literature and the use of single punch analysis has not been fully justified as of yet. Although, there are several manuscripts in the literature that have established the usefulness of single maximal punches to discriminate levels of experience in combat sports. Still, the transfer of single maximal punch analysis to punches thrown in combination and with varying levels of intensity is unknown, remaining a limitation of this work. One of the more fascinating findings of the PhD was the little relative importance of DPMA in determining impact kinetics. While, the evidence provided is strong, it is important to note two methodological differences in this PhD that may have affected the divergence from the literature. First, the method used for the identification of muscle activation start and end were specific to this work, designed to provided quantitative information into DPMA's relationship with impact kinetics. Previous work has identified DPMA through qualitative methods, but has not produced any work related quantitative measure of DPMA. This alone may be the reason for the divergence from the literature. That is, there may be an over emphasis on DPMA due to the qualitative analysis of previous authors. Secondly, is the method used for the normalisation of the EMG signals, MVIC, which has been used in the previous DPMA manuscripts as well. There is the potential that with such low load, high velocity movements, normalisation based off a dynamic maximal voluntary contraction (DMVC) may produce results that yield greater relevance to DPMA. Due to the limited nature of this PhD, such an analysis could not be completed, but there is a gap in the EMG related literature that could be served by the comparison of MVIC and DMVC in low load, high velocity movements. The final limiting factor identified during the process of this PhD research was a completely unavoidable issue, but one that still deserves mention. That is the very process of collecting data via the available technology has an influence on the movement pattern performed. The participants of this research stood upon two elevated force plates, while wearing eight wired EMG electrodes, an EMG transmitter belt, and hit a marked target on a punching bag. There is no way that this amount of equipment did not have some influence on the boxers. Fortunately, whatever impact this had on the boxers appeared to be uniform as seen in the results. These potentially limiting areas of interest are worth noting in the aim of transparency, but are unlikely to have greatly influenced the results of the PhD.

The final summation of this thesis is to answer the question, “What defines effective punching in boxing?” This thesis answered that question by providing evidence that the spring mass model view of a purely ballistic impact is not an accurate representation of effective mass and by extension impact kinetics in punching. Punching is not a ballistic impact, force is applied throughout the impact, produced by the lower body. The paramount importance of the lower body’s production of GRF was repeatedly found through qualitative and quantitative means in this thesis. Using GRF results, punches were defined with phases that highlighted the differences between punch types and provided a framework for future analysis. That framework allowed for an investigation of the determinants of impact kinetics and thus, effective punching.

Synthesis of Findings

The findings of this thesis establish an understanding of punching that differs from that found previously in the literature and understood in popular boxing culture. That is, an effective punch is produced by force application from the lower body to create rotation of a relatively relaxed upper body, transmitting force throughout the entirety of impact. The straight punches are primarily linear movements, that utilizes “blocking” at the hip through high vertical loading and forces applied away from the target by the lead leg to produce hip and thus torso rotation. The hook punches instead rely more on lateral force application from the lower body to create greater rotation throughout the entirety of the punch. Regardless of the punch type, once the lower body has begun the rotation it is continued up the kinetic chain through proper latissimus dorsi activation (activation that is not active for too long or too over active) which finally propels the arm (properly relaxed) to the target. Upon impact the lower body produces GRF to continue applying forces into the target and as such stiffen the body for impact. This method of stiffening differs greatly from that proposed in the literature and is further reinforced by the failure of DPMA to determine the majority of the impact kinetics.

Direction of future research

The findings of this thesis have produced a wide range of questions for future investigations to explore. Areas of interest include:

- A GRF, EMG, and kinematic profile of a common boxing punch known as an uppercut (punches that travel from an inferior to superior position commonly targeting the underside of an opponent's jaw). Such a profile, like the ones created for straight and hook punches would allow for the definition of phases and analysis of determinants of impact kinetics.
- Comparison of lab based measures of impact kinetics to those collected from live boxing matches. The results collected in this thesis are based on an assumption found in the literature, an assumption that lab based testing of impact kinetics have a relationship to impact kinetics in live boxing matches. A comparison between lab based measures and live bouts would confirm the assumption or call into question much of the findings of this thesis.
- Research into the differences between boxing punches and punches found in other combat sports. While comparison between punches from different styles is common in the literature, it is unknown if punching in other combat sports follows the same fundamental pattern as that found in boxing.
- Studies into sport specific strength and conditioning interventions based off the GRF findings of the thesis to improve impact kinetics in boxing. The current literature has been focused on improving maximal strength and power to improve impact kinetics through generalized training. It is likely that using the findings of this thesis would produce greater gains in performance than those produced by generalized training.
- Computer based kinematic and kinetic modelling of the head and body to determine the key impact variables for effective punching Previous literature has attempted to perform analysis to identify key impact kinetics with comparisons between trained and untrained cohorts, but fails to address the specific differences required to damage opponents according to target and outcome goal.

Practical applications

With the knowledge gained from this thesis there are several practical applications for the training of boxers. Regarding the technical training of boxers, the findings from chapters seven and eight indicate that there are substantial differences found between punch types. As such, it is important that boxing coaches train each punch type with that knowledge. Moving forward it is recommended that boxing coaches take time to specifically work on the mechanics of each punch type individually, a practice not commonly performed. Additionally, the findings from Chapter eight may serve to illuminate the areas to focus development on during the proposed technical training.

Practical applications from a strength and conditioning perspective are primarily directed towards a greater focus on the development of lower body force dominant attributes and velocity dominant attributes. The varied demands of the different punch types fail to provide a clear area of focus for the training of force directional application, that is a focus on vertical or horizontal application. Instead it appears the development of both directions is needed, although trained in specific manner for optimization of punching. Force dominant training is needed to improve punching performance through two primary means: first as a method to prepare the boxers for velocity dominant training as identified in the literature, and secondly due to the relatively low rate of force development found in several key determinants. Lower body velocity dominant power development would serve to improve the key determinants of punching that have faster rates of force. The need for greater attention on lower body training does not discount the need for strength and conditioning training of the upper body. Of note, the results of Chapter eight would have practitioners target training of the upper body on velocity dominant power of the triceps and latissimus dorsi. Improved power development in those muscle groups would improve elbow extension velocity and torso rotation. Furthermore, as explained above a biproduct of power training is the speed of relaxation which would improve DPMA, a key determinant of a select few punch types.

In Chapter two it was proposed, based on the literature, that an isometric core training program would improve impact kinetics. The findings from Chapter eight support the proposed intervention. That is, stability in the core aids in the ability to transmit the forces produced by the lower body. Therefore, the recommendations from Chapter two have been proven correct, reinforced with the concepts found throughout the thesis. One finding from Chapter eight that adds to the recommendations of Chapter two is the potential use of the latissimus dorsi to rotate the torso during the punch. With this new information, it is important that strength and conditioning practitioners train not only isometric core strengthening, but large rotational movements like medicine ball throws to train the gross movement pattern of torso rotation. A colleague once said, “rotators gotta rotate”, punching is a clear rotary movement and thus requires rotational training. A form of training that necessitates maximal strength and power from the lower body, transmitted through a stable core musculature, rotating through the torso, and applied through a powerful, yet relaxed arm extension.

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APPENDICES

Appendix 1. Ethics approval and amendment form

A U T E C

S E C R E T A R I A T

18 January 2013

Matt Brughelli

Faculty of Health and Environmental Sciences

Dear Matt

Re Ethics Application: **12/322 Muscular activity and ground reaction forces during punching actions.**

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

Your ethics application has been approved for three years until 17 January 2016.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online throughhttp://www.aut.ac.nz/research/research-ethics/ethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 17 January 2016;
- A brief report on the status of the project using form EA3, which is available online throughhttp://www.aut.ac.nz/research/research-ethics/ethics. This report is to be submitted either when the approval expires on 17 January 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence.

AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Dr Rosemary Godbold

Executive Secretary

Auckland University of Technology Ethics Committee

Cc: Seth Lenetsky lenetsky@gmail.com

27 August 2015

Matt Brughelli

Faculty of Health and Environmental Sciences

Dear Matt

Re: Ethics Application: **12/322 Muscular activity and ground reaction forces during punching actions.**

Thank you for your request for approval of an amendment to your ethics application.

I have approved the minor amendment to your ethics application allowing changes to the inclusion criteria and the data collection protocols.

I remind you that as part of the ethics approval process, you are required to submit the following to the Auckland University of Technology Ethics Committee (AUTEC):

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 17 January 2016;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 17 January 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

K O'Connor

Kate O'Connor

Executive Secretary

Auckland University of Technology Ethics Committee

Cc: Seth Lenetsky lenetsky@gmail.com, Nigel Harris

Appendix 2. Participant information sheets

Participant Information Sheet

Date Information Sheet Produced:
__/__/____

Project Title

Assessing and improving punching forces

An Invitation
Hi, my name is Seth Lenetsky and I am a PhD student at the Auckland University of Technology. As part of my thesis I am doing research on muscular activation and ground reaction forces during punching. Such information could aid in the development of specific strength and conditioning programmes for boxers. To achieve this I need boxers to act as participants to undergo a punching assessment.

What is the purpose of this research?
The purpose of this study is to investigate muscle activation and ground reaction forces of boxers while punching. Specifically, we will investigate timing of muscle contractions during the punch and the direction of the ground reaction forces produced by the legs.
How was I identified and why am I being invited to participate in this research?

To find participants for this I have contact your boxing gym in search of boxers and was put in contact with you by the gym staff. For this study we are looking for uninjured boxers who have trained consistently for at least three years, twice weekly. You do not need to be a competitive boxer only a regular trainee of the sport.

What will happen in this research?
If you choose to participate you will be asked to dress in appropriate attire for exercise (i.e. gym shirt or singlet, shorts or exercise pants). For this study you will need to visit the AUT Millennium Campus where you will be met and taken to the school's biomechanics laboratory. Once in the lab you will be fitted with surface electrodes to monitor muscle activation on the following muscle groups: triceps, latissimus dorsi, rectus abdominis, and rectus femoris. After being fitted with the electrodes you will put on your hand wraps and gloves and will be given a ten minute warm up protocol to prepare you for punching and to calibrate the electrodes. Upon completing the warm up you will be asked to stand on two force plates to monitor your ground reaction forces and will proceed to follow a punching protocol striking a heavy bag maximally. During your time striking the heavy bag a digital video recording will be taken to be analysed with the results from the EMG and force plates.

What are the discomforts and risks?
There should be no significant discomforts or risks beyond those experienced during normal boxing training.

How will these discomforts and risks be alleviated?
Immediately after the punching session you will be able to sit down and rest, and have a drink of water if you desire.

What are the benefits?
It is hoped that this research will benefit boxing as whole by providing findings that will better inform boxing training in the future.

What compensation is available for injury or negligence?
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.

How will my privacy be protected?
The information collected as part of this study will be immediately de-identified, so that any information, features or characteristics that could match you with your data will be removed. This de-identified data will be stored on a secure computer, and only authorised researchers will have access to this data. This information will be published in significant journals, but at no stage will you be identifiable.

What are the costs of participating in this research?
The cost to you as a participant will only by your time, which will not exceed an hour.

What opportunity do I have to consider this invitation?
You can take all the time you need to decide whether you would like to participate in this research.

How do I agree to participate in this research?
To agree to participate in this study all you need to do is complete and sign the attached consent form.

Will I receive feedback on the results of this research?
You will not receive any direct feedback about the results of this study. The reason for this is that at this point I am unsure on what your results will mean in the greater context of the sport of boxing. Once the study has been completed the information gathered will be shared and may serve to influence your later training.

What do I do if I have concerns about this research?
Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Matt Brughelli, matt.brughelli@aut.ac.nz, 09 921 9999 x 7025

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Dr Rosemary Godbold, *rosemary.godbold@aut.ac.nz* , 921 9999 ext 6902.

Whom do I contact for further information about this research?
Researcher Contact Details:

Seth Lenetsky

Email: Lenetsky@gmail.com

Project Supervisor Contact Details:

Matt Brughelli

Email:matt.brughelli@aut.ac.nz

Phone:09 921 9999 x 7025

Approved by the Auckland University of Technology Ethics Committee on *16/12/2015* AUTEC Reference number *12/322*.

Participant Information Sheet

Date Information Sheet Produced: __/__/____

Project Title

Assessing and enhancing punching performance in combat sports athletes

An Invitation

My name is Seth Lenetsky. I am working on a research project at the Auckland University of Technology involving expert coaches' knowledge on the critical factors affecting boxing performance in general and punching in particular. Specifically to break punching into a series of phases to better understand the specifics of effective punching. This is study will also contribute to my PhD.

I would like to invite you to participate in this project as an expert coach. Your experience and knowledge will be integrated with those from other coaches and will inform the other parts of my research. Your participation will be voluntary and you may withdraw at any time.

What is the purpose of this research?

The purpose of this study is to investigate muscle activation, ground reaction forces, and punching force of boxers while punching. Specifically, we will investigate how these measures change throughout the punching action.

How was I identified and why am I being invited to participate in this research?

To find participants for this I have contact your boxing gym in search of coaches and was put in contact with you by the gym staff. For this study we are looking for expert boxing coaches (10+ years of coaching experience).

What will happen in this research?

You will be asked to discuss factors affecting successful punching performance. This will be performed in the context of a short (30-45 minute) interview.

What are the discomforts and risks?

I don't foresee any discomforts and risks except for the length of the interview.

How will these discomforts and risks be alleviated?

We can take breaks as needed. And, if required, we can have a recess and resume at a later time and/or date.

What are the benefits?

is hoped that this research will benefit boxing as whole by providing findings that will better inform boxing training in the future.

How will my privacy be protected?

All videos and transcripts will be kept confidential. Only the aggregate data will be presented, although when necessary, anonymous quotations may be included. All materials generated from the interviews will be seen only by the research team and will be password secured when in electronic form.

What are the costs of participating in this research?

The cost to you as a participant will only by your time, which will take from 30-45 minutes.

What opportunity do I have to consider this invitation?

You can take all the time you need to decide whether you would like to participate in this research

How do I agree to participate in this research?

I will provide you with a Consent Form as soon as you agree to participate.

Will I receive feedback on the results of this research?

You will not receive any direct feedback about the results of this study. The reason for this is that at this point I am unsure on what your results will mean in the greater context of the sport of boxing. Once the study has been completed the information gathered will be shared and may serve to influence your later training.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Matt Brughelli, matt.brughelli@aut.ac.nz, 09 921 9999 x 7025

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , +64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Seth Lenetsky

Email: Lenetsky@gmail.com, *luigi.bercades@gmail.com*, +64 21 0257 1763

Project Supervisor Contact Details:

Matt Brughelli, matt.brughelli@aut.ac.nz, 09 921 9999 x 7025

Approved by the Auckland University of Technology Ethics Committee on *16/12/2015*, AUTEC Reference number *12/322*.

Appendix 3. Participant consent forms

Consent Form

AUT UNIVERSITY
TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Project title: ***Assessing and improving punching forces***

Project Supervisors: ***Matt Brughelli***

Researcher: ***Seth Lenetsky***

- ○ I have read and understood the information provided about this research project in the Information Sheet dated __/__/____.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that I may withdraw myself, or any other information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ○ If I withdraw, I understand that all relevant information will be destroyed.
- ○ I have no injuries or medical conditions that may affect my ability to perform punching actions.
- ○ I agree to take part in this research.
- ○ I wish to receive a copy of the report from the research (please tick one): Yes○ No○
- ○ I understand that the video footage will be used for academic purposes only will not be published in any form outside of this project without my written permission.

Subject's signature: ....

Subject's name: ....

Date: ....

Project Supervisor Contact Details:

Dr Matt Brughelli,

Sports Performance Research Institute New Zealand,

School of Sport and Recreation,

Auckland University of Technology.

Private Bag 92006

Auckland 1020

64 9 921 9999 ext .7025

mbrughelli@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on 16/12/2015 AUTEC

Reference number 12/332

# Consent Form	AUT UNIVERSITY TE WĀNANGA ARONUI O TAMAKI MAKAU RAU

Interviewees

Project title: ***Assessing and enhancing punching performance in combat sports athletes.***

Project Supervisor: ***Matt Brughelli***

Researcher: ***Seth Lenetsky***

- ○ I have read and understood the information provided about this research project in the Information Sheet.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that notes will be taken during the interviews and that they will also be audio taped and transcribed.
- ○ I understand that the videos will be used for academic purposes only and will not be published in any form outside of this project without my written permission.
- ○ I understand 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.
- ○ If I withdraw, I understand that all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- ○ I agree to take part in this research.
- ○ I wish to receive a copy of the report from the research (please tick one): Yes○ No○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

……………………………………………………………………………………..

Date:

Approved by the Auckland University of Technology Ethics Committee on 16/12/2015 AUTEC Reference number 12/322.

Appendix 4. Custom built MATLAB program for the analysis of punch phases and determinant identification

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
 This is the top level of the program.  It is the one that
is run by the %
% user and does the following process:
%
%   Create a list of users for data processing
%
%   Move into that folder
%
%   Process the csv files to load the data into the data
structure        %
%   Calculate the MVIC data for each athlete
%
%
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%


% Set the working directory
cd ('D:\SPRINZ\Boxing Data');

% Sets the path for the Matlab file locations
path(path,'D:\SPRINZ\Boxing Data');

% Clear the workspace plots and command window
clear all; close all; clc;

% Create a list of folders
fList=ls;                                     % list all
files and folders
j=1;                                          % counter for
identified folders
for i=1:length(fList)                         % loop through
all files and folders
    if regexp(fList(i,:),'Trained')           % check if its
a Trained folder
        folderList(j,:)=fList(i,:);           % keep that
folder in the folder list
        j=j+1;                                % increment the
new list
    end
end

% Set up the data structure to hold all the athlete data
data=[];

% Loop through each folder and call the matlab files to
extract the data and calculate MVIC
```

```
[folder_No,~]=size(folderList);              % get the
number of Trained folders
p_num=1;                                     % set the
playre number being processed to 1
for i=1:folder_No                            % loop through
each folder
    cd(folderList(i,:));                     % chage to the
folder for processing
    disp(['Processing Folder: ' folderList(i,:)]); % Tell
the user the folder thats being processed
    fileList=ls;                             % create a list
of the files in that folder
    [file_No,~]=size(fileList);              % find out how
many files there are


%   Only needed for when Untrained is being investigated
%     subfolder_flag=0;                         % flag used
to identify if subfolders exist
%     for j=1:file_No                           % Loop for
each file or folder
%         if regexp(fileList(j,:),'Session')    % Check the
file or folder for the word 'Session'
%             subfolder_flag=1;                 % Trigger the
subfolder flag if Session is found
%         end
%     end
%
%     if subfolder_flag
%         cd('Session1')
%         file_process(a,b,b1,c,d,d1);
%         cd('..')
%         cd('Session2');
%         file_process(a,b,b1,c,d,d1);
%         cd('..');
%
%     else
%
%     end

    % Extract the data from the CSV files into the athlete
structure
    data=file_process2(p_num,data,i);

    % process MVIC Data
    data=mvic_load(p_num,data,i);               % Call the
matlab function to calculate MVIC
    disp('MVIC Complete')                    % Tell the user
that this has been done
    disp(data.pID(p_num).mvic)               % Tell the user
which person was complete

    cd('..')                       % Return to the top folder
```

```
    p_num=p_num+1;              % Incerement the player
track being processed.
end


clear all; close all; clc;

colour=jet(7);

punchType={'Cross','Jab','LHook','RHook'};

load('data6.mat');
load('raw_data.mat');

warning('off','signal:findpeaks:largeMinPeakHeight');

plot_all=1;
plot_player_mean=1;
plot_global_mean=1;
remove_dodgy_emg_channels=1;

mvic_thresh=0.10;

windowSize=2000;
windowOffset=-500;
timeSeries=(-
windowSize/2)+windowOffset:(windowSize/2)+windowOffset;
plotOffset=(windowSize/2);

phase2_search_start=1000;
phase2_search_end=1500;
phase1_search_start=1150;
phase1_search_end=1000;

l=1;
fID=fopen('test8.txt','w');

timeSeries=-1.5:0.001:0.5;

emg_peak_thresh=0.4;

n=1;

[b1,a1] = butter(4,[0.02 0.9],'bandpass');
[b2,a2] = butter(4,0.006,'low');

%dodgy emg channels
for i=1:4
    for j=1:10
        pu(i).pID(j).c_keep=1:7;
    end
end

pu(1).pID(1).c_keep=2:7;
```

```
pu(1).pID(3).c_keep=[1 4:7];
pu(1).pID(6).c_keep=[1:4 6:7];
pu(1).pID(7).c_keep=3:7;
pu(1).pID(10).c_keep=1:6;

pu(2).pID(5).c_keep=4:7;
pu(2).pID(7).c_keep=[2 4:5 7];

pu(3).pID(2).c_keep=1:5;
pu(3).pID(5).c_keep=2:7;

pu(4).pID(1).c_keep=2:7;
pu(4).pID(2).c_keep=3:7;
pu(4).pID(4).c_keep=[1:3 5:7];

for i=1%:4 % number of punch types
    for j=1:10 %number of players
        for
k=3:length(raw_data.punch_type(i).pID(j).punch_no) %number
of punches

tempdataFf=raw_data.punch_type(i).pID(j).punch_no(k).ff;

tempdataBf=raw_data.punch_type(i).pID(j).punch_no(k).bf;

trial(k).emg_data=raw_data.punch_type(i).pID(j).punch_no(k)
.emg;

            figure();
            for channel=1:8 % EMG Channel select

trial(k).emg_data_filt_1(:,channel)=filtfilt(b1,a1,trial(k)
.emg_data(:,channel));

trial(k).emg_data_filt_2(:,channel)=filtfilt(b2,a2,abs(tria
l(k).emg_data_filt_1(:,channel)))/data.pID(j).mvic(channel)
;


test_data=trial(k).emg_data_filt_2(:,channel);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%% diff method
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%                  test_data_d=diff(test_data);
%                  test_data_dd=diff(test_data_d);
%                  figure();
%                  ax(1)=subplot(3,1,1);
%                  plot(test_data)
%                  xlim([0,2000]);
%                  ax(2)=subplot(3,1,2);
%                  plot(test_data_d);
%                  xlim([0,2000]);
%                  ax(3)=subplot(3,1,3);
```

```
%                  plot(test_data_dd);
%                  xlim([0,2000]);

%%%%%%%%%%%%%%%%%%%%%%% n * STD static method
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%                  std_n=8;
%
%                  window_val=mean(test_data(1:100));
%                  window_std=std(test_data(1:100));
%
%                  active_level=0;
%                  for wind=500:50:length(test_data)-50
%                      if active_level==0 &&
mean(test_data(wind:wind+49)) > window_val +
(std_n*window_std)
%
active_level=mean(test_data(wind:wind+49));
%                      end
%                  end
%
%                  active_time=zeros(1,length(test_data));
%                  active_time(test_data>=active_level)=1;
%
%                  figure(((i-1)*8)+channel);
%                  hold on;
%                  plot(test_data,'Color',colour(k,:))
%                  hold on;
%                  plot(active_time*(1-
(k*0.05)),'Color',colour(k,:));

%%%%%%%%%%%%%%%%%%%%%%%%%% n * STD method
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%                  std_n=8;
%
%                  window_val=mean(test_data(1:49));
%                  window_std=std(test_data(1:49));
%
%                  active_level=0;
%                  for wind=50:50:length(test_data)-50
%                      if active_level==0 &&
mean(test_data(wind:wind+49)) > (window_val +
(std_n*window_std))
%
active_level=mean(test_data(wind:wind+49));
%                      end
%
window_val=mean(test_data(wind:wind+49));
%
window_std=std(test_data(wind:wind+49));
%                  end
%
```

```
%                   active_time=zeros(1,length(test_data));
%                   active_time(test_data>=active_level)=1;
%
%                   figure();
%                   plot(test_data)
%                   hold on;
%                   plot(active_time,'r');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% n percent of peak
%%%%%%%%%%%%%%%%%%%%%%%%%%

%                   perc=0.10;
%                   active_time=zeros(1,length(test_data));
%
active_time(test_data>max(test_data)*perc)=1;
%
%                   figure(((i-1)*8)+channel);
%                   hold on;
%                   plot(test_data,'Color',colour(k,:))
%                   hold on;
%                   plot(active_time*(1-
(k*0.05)),'Color',colour(k,:));
%
%%%%%%%%%%%%%%%%%%%%%%%%%%% n threshold of mvic
%%%%%%%%%%%%%%%%%%%%%%%%%%%
%


                if i==1 %cross punch

                    % PHASE DEFINITIONS
                    % PHASE 1
                    %   Start = 10% drop from the max of
the y-axis front foot prior to impact (before phase 2)
                    %   End   = Minimum of y-axis front
foot prior to impact
                    % PHASE 2
                    %   Start = Minimum of the y-axis front
foot prior to impact
                    %   End   = Impact start as defined in
Seth's excel document
                    % PHASE 3 (IMPACT)
                    %   Start = Impact start as defined in
Seth's excel document
                    %   End   = Impact start plus duration
as defined in Seth's excel document


[cross_pTwoMin,pos]=min(tempdataFf(phase2_search_start:phas
e2_search_end,2));

phase_two=timeSeries(pos+phase2_search_start);
```

```
[cross_pOneMax,pos2]=max(tempdataFf(phase1_search_start:pos
+phase1_search_end,2));

phase_ones=find(tempdataFf(phase1_search_start+pos2:pos+pha
se1_search_start,2) <= cross_pTwoMin+(abs(cross_pOneMax-
cross_pTwoMin)*0.9));

phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);
                    temp_data=[tempdataFf tempdataBf];


phase1_data=temp_data(phase_ones(1)+phase1_search_start+pos
2:pos+phase1_search_end,:);

phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
                    phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(1).time.duration,:);
                end
                if i==2 %jab punch

                    % PHASE DEFINITIONS
                    % PHASE 1
                    %   Start = 10% drop from the max of
the z-axis back foot prior to impact (before phase 2)
                    %   End   = Minimum of z-axis back foot
prior to impact
                    % PHASE 2
                    %   Start = Minimum of the z-axis back
foot prior to impact
                    %   End   = Impact start as defined in
Seth's excel document
                    % PHASE 3 (IMPACT)
                    %   Start = Impact start as defined in
Seth's excel document
                    %   End   = Impact start plus duration
as defined in Seth's excel document


[jab_pTwoMin,pos]=min(tempdataBf(phase2_search_start:phase2
_search_end,3));

phase_two=timeSeries(pos+phase2_search_start);
                    temp_data=[tempdataFf tempdataBf];


[jab_pOneMax,pos2]=max(tempdataBf(phase1_search_start:pos+p
hase1_search_end,3));

phase_ones=find(tempdataBf(phase1_search_start+pos2:pos+pha
```

```
se1_search_start,3) <= jab_pTwoMin+(abs(jab_pOneMax-
jab_pTwoMin)*0.9));

phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);


phase1_data=temp_data(phase_ones(1)+phase1_search_start+pos
2:pos+phase1_search_end,:);

phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
                    phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);

                end

                if i==3 %LHook

                    % PHASE DEFINITIONS
                    % PHASE 1
                    %   Start = crossover in z-axis as
weight goes onto front foot
                    %   End   = cross over in y-axis
                    % PHASE 2
                    %   Start = cross over in y-axis
                    %   End   = peak in the x-axis front
foot prior to impact
                    % PHASE 3
                    %   Start = peak in the x-axis front
foot prior to impact
                    %   End   = Impact start as defined in
Seth's excel document
                    % PHASE 4 (IMPACT)
                    %   Start = Impact start as defined in
Seth's excel document
                    %   End   = Impact start plus duration
as defined in Seth's excel document


[lhook_pThreeMax,pos]=max(tempdataFf(1200:1500,1))
                    if pos>=290

[lhook_pThreeMax,pos]=max(tempdataFf(1300:1450,1))
                        phase_three=timeSeries(pos+1300);
                    else
                        phase_three=timeSeries(pos+1200);
                    end
```

```
[lhook_pTwoMin,pos2]=min(abs(tempdataFf(800:pos+1200,2)-
tempdataBf(800:pos+1200,2)));
                    phase_two=timeSeries(pos2+800);


[lhook_pOne,temp_pos]=max([tempdataFf(pos2+750,3)
tempdataBf(pos2+750,3)]);
                    pos1=0;
                    if temp_pos==1 %Front foot is higher
                        for count=pos2+750:-1:1
                            if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
                                pos1=count;
                            end
                        end
                    else
                        for count=pos2+750:-1:1
                            if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
                                pos1=count;
                            end
                        end
                    end
                    if pos1 ==0

[mag,pos1]=min(abs(tempdataFf(1:pos2+750,3)-
tempdataBf(1:pos2+750,3)));
                    end
                    phase_one=timeSeries(pos1);


                    temp_data=[tempdataFf tempdataBf];

                    phase1_data=temp_data(pos1:pos2+800,:);

phase2_data=temp_data(pos2+800:pos+1200,:);

phase3_data=temp_data(pos+1200:plotOffset-windowOffset,:);
                    phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);
                end

                if i==4 %RHook

                    % PHASE DEFINITIONS
                    % PHASE 1
                    %   Start = crossover in z-axis as
weight goes onto back foot
                    %   End   = 10% drop in y-axis front
foot
                    % PHASE 2
```

```
                    %   Start = 10% drop in y-axis front
foot
                    %   End   = minimum in y-axis front
foot
                    % PHASE 3
                    %   Start = minimum in y-axis front
foot
                    %   End   = Impact start as defined in
Seth's excel document
                    % PHASE 4 (IMPACT)
                    %   Start = Impact start as defined in
Seth's excel document
                    %   End   = Impact start plus duration
as defined in Seth's excel document



[rhook_pThreeMin,pos]=min(tempdataFf(1000:1500,2));
                    phase_three=timeSeries(pos+1000);


[rhook_pTwoMax,pos2]=max(tempdataFf(1150:pos+1000,2));

phase_twos=find(tempdataFf(1150+pos2:pos+1150,2) <=
rhook_pThreeMin+(abs(rhook_pTwoMax-rhook_pThreeMin)*0.9));

phase_two=timeSeries(phase_twos(1)+1150+pos2);


[rhook_pOne,temp_pos]=max([tempdataFf(pos2+1150,3)
tempdataBf(pos2+1150,3)]);
                    pos1=0;
                    if temp_pos==1 %Front foot is higher
                        for count=phase_twos(1)+1150+pos2:-
1:1
                            if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
                                pos1=count;
                            end
                        end
                    else
                        for count=phase_twos(1)+1150+pos2:-
1:1
                            if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
                                pos1=count;
                            end
                        end
                    end
                    if pos1 ==0

[mag,pos1]=min(abs(tempdataFf(phase_twos(1)+1150+pos2,3)-
tempdataBf(phase_twos(1)+1150+pos2,3)));
```

```
                    end
                    phase_one=timeSeries(pos1);


                    temp_data=[tempdataFf tempdataBf];


phase1_data=temp_data(pos1:phase_twos(1)+1150+pos2,:);

phase2_data=temp_data(phase_twos(1)+1150+pos2:pos+1000,:);

phase3_data=temp_data(pos+1000:plotOffset-windowOffset,:);
                    phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);

                end



                active_time=zeros(1,length(test_data));
                active_time(test_data>mvic_thresh)=1;

                s_acti=find(diff(active_time)==1);
                f_acti=find(diff(active_time)==-1);

                if length(s_acti)<length(f_acti)
                    s_acti=[1 s_acti];
                elseif length(f_acti)<length(s_acti)
                    f_acti=[f_acti length(active_time)-1];
                end

                time_x=-1.5:0.001:0.5;
                ax(channel)=subplot(4,2,channel);
                plot(time_x,test_data,'k','Linewidth',2)
                hold on;

plot(time_x,tempdataFf(:,4)/max(tempdataFf(:,4))*max(test_d
ata),'--b');

plot(time_x,tempdataBf(:,4)/max(tempdataBf(:,4))*max(test_d
ata),'--r');


                peak_m=[];
                peak_loc=[];
                mean_acti=[];
                imp_acti=[];
                ph_start=[];
                ph_peak=[];
                ph_end=[];

                for box=1:length(s_acti)
```

```
                    p=patch([time_x(s_acti(box))
time_x(s_acti(box)) time_x(f_acti(box))
time_x(f_acti(box))],[0 max(test_data)*1.2
max(test_data)*1.2 0],'g','FaceAlpha',0.4,'EdgeColor','k');
                    [pk
lk]=max(test_data(s_acti(box):f_acti(box)));
                    peak_m=[peak_m pk];
                    peak_loc=[peak_loc s_acti(box)+lk];
                    mean_acti=[mean_acti
mean(test_data(s_acti(box):f_acti(box)))];
                    imp_acti=[imp_acti
trapz(test_data(s_acti(box):f_acti(box)))/1000];
                    if i==1||i==2
                        if time_x(s_acti(box)+lk)<phase_one
                            ph_pk=-100;
                        elseif
time_x(s_acti(box)+lk)<phase_two
                            ph_pk=1;
                        elseif time_x(s_acti(box)+lk)<0
                            ph_pk=2;
                        elseif
time_x(s_acti(box)+lk)<data.pID(j).type(i).punch(1).time.du
ration
                            ph_pk=100;
                        else
                            ph_pk=1000;
                        end

                        if time_x(s_acti(box))<phase_one
                            ph_s=-100;
                        elseif
time_x(s_acti(box))<phase_two
                            ph_s=1;
                        elseif time_x(s_acti(box))<0
                            ph_s=2;
                        elseif
time_x(s_acti(box))<data.pID(j).type(i).punch(1).time.durat
ion
                            ph_s=100;
                        else
                            ph_s=1000;
                        end

                        if time_x(f_acti(box))<phase_one
                            ph_f=-100;
                        elseif
time_x(f_acti(box))<phase_two
                            ph_f=1;
                        elseif time_x(f_acti(box))<0
                            ph_f=2;
                        elseif
time_x(f_acti(box))<data.pID(j).type(i).punch(1).time.durat
ion
```

```
                                ph_f=100;
                            else
                                ph_f=1000;
                            end
                        else
                            if time_x(s_acti(box)+lk)<phase_one
                                ph_pk=-100;
                            elseif
time_x(s_acti(box)+lk)<phase_two
                                ph_pk=1;
                            elseif
time_x(s_acti(box)+lk)<phase_three
                                ph_pk=2;
                            elseif time_x(s_acti(box)+lk)<0
                                ph_pk=3;
                            elseif
time_x(s_acti(box)+lk)<data.pID(j).type(i).punch(1).time.du
ration
                                ph_pk=100;
                            else
                                ph_pk=1000;
                            end

                            if time_x(s_acti(box))<phase_one
                                ph_s=-100;
                            elseif
time_x(s_acti(box))<phase_two
                                ph_s=1;
                            elseif
time_x(s_acti(box))<phase_three
                                ph_s=2;
                            elseif time_x(s_acti(box))<0
                                ph_s=3;
                            elseif
time_x(s_acti(box))<data.pID(j).type(i).punch(1).time.durat
ion
                                ph_s=100;
                            else
                                ph_s=1000;
                            end

                            if time_x(f_acti(box))<phase_one
                                ph_f=-100;
                            elseif
time_x(f_acti(box))<phase_two
                                ph_f=1;
                            elseif
time_x(f_acti(box))<phase_three
                                ph_f=2;
                            elseif time_x(f_acti(box))<0
                                ph_f=3;
```

```
                        elseif
time_x(f_acti(box))<data.pID(j).type(i).punch(1).time.durat
ion
                            ph_f=100;
                        else
                            ph_f=1000;
                        end
                    end

                    ph_start=[ph_start ph_s];
                    ph_peak=[ph_peak ph_pk];
                    ph_end=[ph_end ph_f];
                end

                y_val=ylim;
                ylim([max([y_val(1) -0.1]) y_val(2)]);

                line([phase_two phase_two],ylim);
                line([phase_one phase_one],ylim);

line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration]/1000,ylim);
                if i==3 || i==4
                    line([phase_three phase_three],ylim);
                end


ptype(i).pID(j).trial(k).emg_channel(channel).peak_m=peak_m
;

ptype(i).pID(j).trial(k).emg_channel(channel).peak_loc=peak
_loc;

ptype(i).pID(j).trial(k).emg_channel(channel).start=s_acti;

ptype(i).pID(j).trial(k).emg_channel(channel).finish=f_acti
;

ptype(i).pID(j).trial(k).emg_channel(channel).duration=f_ac
ti-s_acti;




fprintf(fID,'%s,%s,%s,%s',num2str(i),num2str(j),num2str(k),
num2str(channel));

                for pp=1:length(peak_m)

fprintf(fID,',%s,%s,%s,%s',num2str(peak_m(pp)),num2str(time
_x(peak_loc(pp))),num2str(time_x(s_acti(pp))),num2str(time_
x(f_acti(pp))));
```

```
fprintf(fID,',%s,%s,%s,%s',num2str((peak_loc(pp)-
s_acti(pp))/1000), num2str((f_acti(pp)-
s_acti(pp))/1000),num2str(mean_acti(pp)),num2str(imp_acti(p
p)));

fprintf(fID,',%s,%s,%s',num2str(ph_start(pp)),num2str(ph_pe
ak(pp)),num2str(ph_end(pp)));
                end

                fprintf(fID,'\n');


%%%%%%%%%%%% Peak detection followed by  10% diff between
peak and trough
%
[peaks,locs]=findpeaks(test_data);%,'MinPeakHeight',mean(te
st_data)+2*std(test_data));
%                 [neg_peaks,neg_locs]=findpeaks(-
test_data);
%
%                 low_mean=mean(test_data(1:500));
%                 [high_val,high_loc]=max(test_data);
%
%                 %if high_val>0.05
%
onset=find(test_data(1:high_loc)<=low_mean+(high_val-
low_mean)*0.1);
%                     if isempty(onset)
%                         onset=1;
%                     else
%                         onset=onset(end);
%                     end
%
%                     low_mean=mean(test_data(1800:2000));
%
offset=find(test_data(high_loc:end)<=low_mean+(high_val-
low_mean)*0.1);
%                     if isempty(offset)
%                         offset=2000;
%                     else
%                         offset=offset(1)+high_loc;
%                     end
%
%
sig_peaks=peaks(find(peaks>=(max(peaks)*emg_peak_thresh)));
%
sig_locs=locs(find(peaks>=(max(peaks)*emg_peak_thresh)));
%
%                     [active_peaks,
active_locs]=findpeaks(test_data(onset:offset));
%
```

```
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak_m=active
_peaks;
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak_loc=acti
ve_locs+onset;
%
ptype(i).pID(j).trial(k).emg_channel(channel).s_trough=test
_data(onset);
%
ptype(i).pID(j).trial(k).emg_channel(channel).s_trough_loc=
onset;
%
ptype(i).pID(j).trial(k).emg_channel(channel).e_trough=test
_data(offset);
%
ptype(i).pID(j).trial(k).emg_channel(channel).e_trough_loc=
offset;
%
%
%
fprintf(fID,'%s,%s,%s,%s,%s,%s',num2str(i),num2str(j),num2s
tr(k),num2str(channel),num2str(onset),num2str(offset));
%                      for pks=1:length(active_peaks)
%
fprintf(fID,',%s,%s',num2str(active_peaks(pks)),num2str(act
ive_locs(pks)+onset));
%                      end
%                      fprintf(fID,'\n');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%


%                  else
%
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak_m=0;
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak_loc=0;
%
ptype(i).pID(j).trial(k).emg_channel(channel).s_trough=0;
%
ptype(i).pID(j).trial(k).emg_channel(channel).s_trough_loc=
0;
%
ptype(i).pID(j).trial(k).emg_channel(channel).e_trough=0;
%
ptype(i).pID(j).trial(k).emg_channel(channel).e_trough_loc=
0;
%                  end
%%%%%%%%%%%%%%%%%%%%%%%%%% PRINT OUTPUTS TO CSV FILE
%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% %
fprintf(fID,'%s,%s,%s,%s',num2str(i),num2str(j),num2str(k),
num2str(channel));
%                  for sig=1:length(sig_peaks)
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak(sig).pea
k=[sig_locs(sig), test_data(sig_locs(sig))];
%
%                      la= num2str(sig_locs(sig));
%                      lb=num2str(test_data(sig_locs(sig)));
%
%
temp_peaks=find(neg_locs<sig_locs(sig));
%                      if isempty(temp_peaks)
%                          out=1;
%                      else
%                          out=neg_locs(max(temp_peaks));
%                      end
%
s_offset=find(test_data(out:sig_locs(sig))>(((sig_peaks(sig
)-test_data(out))*0.1)+test_data(out)));
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak(sig).s_t
rough=[out+s_offset(1),test_data(out+s_offset(1))];
%
%                      lc=num2str(out+s_offset(1));
%
ld=num2str(test_data(out+s_offset(1)));
%
%
temp_peaks=find(neg_locs>sig_locs(sig));
%                      if isempty(temp_peaks)
%                          out=length(test_data);
%                      else
%                          out=neg_locs(min(temp_peaks));
%                      end
%
%
e_offset=find(test_data(sig_locs(sig):out)>(((sig_peaks(sig
)-test_data(out))*0.1)+test_data(out)));
%
ptype(i).pID(j).trial(k).emg_channel(channel).peak(sig).e_t
rough=[sig_locs(sig)+e_offset(end),test_data(sig_locs(sig)+
e_offset(end))];
%
%
le=num2str(sig_locs(sig)+e_offset(end));
%
lf=num2str(test_data(sig_locs(sig)+e_offset(end)));
%
%
%
fprintf(fID,',%s,%s,%s,%s,%s,%s',la,lb,lc,ld,le,lf);
```

```
%
%                 end
%                fprintf(fID,'\n');
            end

        end
%
emg_channel_data=reshape([trial.emg_data_filt_2],2001,8,7);
%
%         if plot_all
%             figure()
%             for channel=1:8
%                 ax(channel)=subplot(4,2,channel);
%                 hold on;
%
plot(squeeze(emg_channel_data(:,channel,pu(i).pID(j).c_keep
)*100));
%             end
%
%             for k=pu(i).pID(j).c_keep
%                 for channel=1:8
% %                     if
~isempty(ptype(i).pID(j).trial(k).emg_channel(channel).peak
(1).peak)
% %                         for
peaks=1:length(ptype(i).pID(j).trial(k).emg_channel(channel
).peak)
%
scatter(ax(channel),ptype(i).pID(j).trial(k).emg_channel(ch
annel).peak_loc,ptype(i).pID(j).trial(k).emg_channel(channe
l).peak_m*100)
%
scatter(ax(channel),ptype(i).pID(j).trial(k).emg_channel(ch
annel).s_trough_loc,ptype(i).pID(j).trial(k).emg_channel(ch
annel).s_trough*100)
%
scatter(ax(channel),ptype(i).pID(j).trial(k).emg_channel(ch
annel).e_trough_loc,ptype(i).pID(j).trial(k).emg_channel(ch
annel).e_trough*100)
% %                         end
% %                     end
%                 end
%             end
%         end

%
player_mean(j).ff_data=mean(reshape([trial.ff_data],2001,4,
7),3);
%
player_mean(j).bf_data=mean(reshape([trial.bf_data],2001,4,
7),3);
%
%
```

```
%          for channel=1:8
%
player_mean(j).emg_mean(:,channel)=mean(squeeze(emg_channel
_data(:,channel,pu(i).pID(j).c_keep)),2);
%
player_mean(j).emg_std(:,channel)=std(squeeze(emg_channel_d
ata(:,channel,pu(i).pID(j).c_keep))');
%          end



%          if plot_player_mean
%              figure()
%              for channel=1:8
%                  ax(channel)=subplot(4,2,channel);
%                  hold on;
%
plot(player_mean(j).emg_mean(:,channel)*100);
%
plot(player_mean(j).emg_mean(:,channel)*100+player_mean(j).
emg_std(:,channel)*100,'r:');
%
plot(player_mean(j).emg_mean(:,channel)*100-
player_mean(j).emg_std(:,channel)*100,'r:');
%              end
%          end

    end
%
all_mean(i).ff_data=mean(reshape([player_mean.ff_data],2001
,4,10),3);
%
all_mean(i).bf_data=mean(reshape([player_mean.bf_data],2001
,4,10),3);
%
%
emg_mean_channel_data=reshape([player_mean.emg_mean],2001,8
,10);
%
%      for channel=1:8
%
all_mean(i).emg_mean(:,channel)=mean(squeeze(emg_mean_chann
el_data(:,channel,:)),2);
%
all_mean(i).emg_std(:,channel)=std(squeeze(emg_mean_channel
_data(:,channel,:))');
%      end
%
%      if plot_global_mean
%          figure()
%          for channel=1:8
%              ax(channel)=subplot(4,2,channel);
```

```
%
temp_emg_channel=squeeze(emg_mean_channel_data(:,channel,:)
);
%              for k=1:10
%                  hold on;
%
plot(timeSeries,temp_emg_channel(:,k)*100);
%              end
%
%          end
%          figure()
%          for channel=1:8
%              ax(channel)=subplot(4,2,channel);
%              hold on;
%
plot(timeSeries,all_mean(i).emg_mean(:,channel)*100);
%
plot(timeSeries,all_mean(i).emg_mean(:,channel)*100+all_mea
n(i).emg_std(:,channel)*100,'r:');
%
plot(timeSeries,all_mean(i).emg_mean(:,channel)*100-
all_mean(i).emg_std(:,channel)*100,'r:');
%
%          end
%      end

end
fclose(fID);


%              %EMG calculations
%              [trials,~]=size(emgff_1);
%              for a=1:trials
%
[peaks,locs]=findpeaks(emgff_1(a,:),'MinPeakHeight',mean(em
gff_1(a,:))+2*std(emgff_1(a,:)));
%                      [neg_peaks,neg_locs]=findpeaks(-
emgff_1(a,:));
%
%
sig_peaks=peaks(find(peaks>=max(peaks)*emg_peak_thresh));
%
sig_locs=locs(find(peaks>=max(peaks)*emg_peak_thresh));
%
%                      for sig=1:length(sig_peaks)
%
ptype(i).pID(j).trial(a).peaks_1(sig).peak=[locs(find(peaks
>=max(peaks)*emg_peak_thresh)),
peaks(find(peaks>=max(peaks)*emg_peak_thresh))];
%
temp_peaks=find(neg_locs<sig_locs(sig));
%                          if isempty(temp_peaks)
%                              out=1;
```

```
%                          else
%
out=neg_locs(max(temp_peaks));
%                          end
%
ptype(i).pID(j).trial(a).peaks_1(sig).s_trough=[out,emgff_1
(a,out)];
%
%
temp_peaks=find(neg_locs>sig_locs(sig));
%                          if isempty(temp_peaks)
%                              out=length(emgff_1(a,:));
%                          else
%
out=neg_locs(min(temp_peaks));
%                          end
%
ptype(i).pID(j).trial(a).peaks_1(sig).e_trough=[out,emgff_1
(a,out)];
%                      end
%              end
%
%              [trials,~]=size(emgff_2);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_2(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_2=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_2=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_3);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_3(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_3=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_3=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_4);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_4(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_4=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
```

```
%
ptype(i).pID(j).trial(a).locs_4=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_5);
%              for a=1:trials
%
[peaks,locs]=findpeaks(emgff_5(a,:),'MinPeakHeight',mean(em
gff_1(a,:))+2*std(emgff_1(a,:)));
%
%
ptype(i).pID(j).trial(a).peaks_5=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_5=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_6);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_6(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_6=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_6=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_7);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_7(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_7=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_7=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%              [trials,~]=size(emgff_8);
%              for a=1:trials
%                      [peaks,locs]=findpeaks(emgff_8(a,:));
%
%
ptype(i).pID(j).trial(a).peaks_8=peaks(find(peaks>=max(peak
s)*emg_peak_thresh));
%
ptype(i).pID(j).trial(a).locs_8=locs(find(peaks>=max(peaks)
*emg_peak_thresh));
%              end
%
%          emg_mean_1(j,:)=mean(emgff_1);
%          emg_mean_2(j,:)=mean(emgff_2);
```

```
%           emg_mean_3(j,:)=mean(emgff_3);
%           emg_mean_4(j,:)=mean(emgff_4);
%           emg_mean_5(j,:)=mean(emgff_5);
%           emg_mean_6(j,:)=mean(emgff_6);
%           emg_mean_7(j,:)=mean(emgff_7);
%           emg_mean_8(j,:)=mean(emgff_8);
%
%           if print_individual_means
%               figure();
%               suptitle(sprintf('%s pID: %i
EMG\n',punchType{i},j));
%               ax(1)=subplot(421);
%               plot(emgff_1'); title('1');
%               hold on;
%               for a=1:length(ptype(i).pID(j).trial)
%                   for
sig=1:length(ptype(i).pID(j).trial(a).peaks_1)
%
scatter(ptype(i).pID(j).trial(a).peaks_1(sig).peak(1),ptype
(i).pID(j).trial(a).peaks_1(sig).peak(2))
%
scatter(ptype(i).pID(j).trial(a).peaks_1(sig).s_trough(1),p
type(i).pID(j).trial(a).peaks_1(sig).s_trough(2))
%
scatter(ptype(i).pID(j).trial(a).peaks_1(sig).e_trough(1),p
type(i).pID(j).trial(a).peaks_1(sig).e_trough(2))
%
%scatter(ptype(i).pID(j).trial(a).locs_1,ptype(i).pID(j).tr
ial(a).peaks_1)
%                   end
%               end
%
%               ax(2)=subplot(422);
%               plot(emgff_2'); title('2');
%               hold on;
%               for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_2,ptype(i).pID(j).tri
al(a).peaks_2)
%               end
%
%               ax(3)=subplot(423);
%               plot(emgff_3'); title('3');
%               hold on;
%               for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_3,ptype(i).pID(j).tri
al(a).peaks_3)
%               end
%
%               ax(4)=subplot(424);
%               plot(emgff_4'); title('4');
%               hold on;
```

```
%             for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_4,ptype(i).pID(j).tri
al(a).peaks_4)
%             end
%
%             ax(5)=subplot(425);
%             plot(emgff_5'); title('5');
%             hold on;
%             for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_5,ptype(i).pID(j).tri
al(a).peaks_5)
%             end
%
%             ax(6)=subplot(426);
%             plot(emgff_6'); title('6');
%             hold on;
%             for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_6,ptype(i).pID(j).tri
al(a).peaks_6)
%             end
%
%             ax(7)=subplot(427);
%             plot(emgff_7'); title('7');hold on;
%             for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_7,ptype(i).pID(j).tri
al(a).peaks_7)
%             end
%
%             ax(8)=subplot(428);
%             plot(emgff_8'); title('8');
%             hold on;
%             for a=1:length(ptype(i).pID(j).trial)
%
scatter(ptype(i).pID(j).trial(a).locs_8,ptype(i).pID(j).tri
al(a).peaks_8)
%             end
%
%             figure()
%             suptitle(sprintf('%s pID: %i EMG Mean and
STD\n',punchType{i},j));
%             ax(1)=subplot(421);
%             plot(mean(emgff_1));hold on; title('1');
%             plot(mean(emgff_1)+std(emgff_1),':r')
%             plot(mean(emgff_1)-std(emgff_1),':r')
%             ax(2)=subplot(422);
%             plot(mean(emgff_2));hold on; title('2');
%             plot(mean(emgff_2)+std(emgff_2),':r')
%             plot(mean(emgff_2)-std(emgff_2),':r')
%             ax(3)=subplot(423);
```

```
%              plot(mean(emgff_3));hold on; title('3');
%              plot(mean(emgff_3)+std(emgff_3),':r')
%              plot(mean(emgff_3)-std(emgff_3),':r')
%              ax(4)=subplot(424);
%              plot(mean(emgff_4));hold on; title('4');
%              plot(mean(emgff_4)+std(emgff_4),':r')
%              plot(mean(emgff_4)-std(emgff_4),':r')
%              ax(5)=subplot(425);
%              plot(mean(emgff_5));hold on; title('5');
%              plot(mean(emgff_5)+std(emgff_5),':r')
%              plot(mean(emgff_5)-std(emgff_5),':r')
%              ax(6)=subplot(426);
%              plot(mean(emgff_6));hold on; title('6');
%              plot(mean(emgff_6)+std(emgff_6),':r')
%              plot(mean(emgff_6)-std(emgff_6),':r')
%              ax(7)=subplot(427);
%              plot(mean(emgff_7));hold on; title('7');
%              plot(mean(emgff_7)+std(emgff_7),':r')
%              plot(mean(emgff_7)-std(emgff_7),':r')
%              ax(8)=subplot(428);
%              plot(mean(emgff_8));hold on; title('8');
%              plot(mean(emgff_8)+std(emgff_8),':r')
%              plot(mean(emgff_8)-std(emgff_8),':r')
%          end
%      end
%
%      ff_data_mean_mean_x(j,:)=mean(ff_data_mean_x);
%      ff_data_mean_mean_y(j,:)=mean(ff_data_mean_y);
%      ff_data_mean_mean_z(j,:)=mean(ff_data_mean_z);
%      ff_data_mean_mean_m(j,:)=mean(ff_data_mean_m);
%      bf_data_mean_mean_x(j,:)=mean(bf_data_mean_x);
%      bf_data_mean_mean_y(j,:)=mean(bf_data_mean_y);
%      bf_data_mean_mean_z(j,:)=mean(bf_data_mean_z);
%      bf_data_mean_mean_m(j,:)=mean(bf_data_mean_m);
%
%      emg_mean_mean_1(j,:)=mean(emg_mean_1);
%      emg_mean_mean_2(j,:)=mean(emg_mean_2);
%      emg_mean_mean_3(j,:)=mean(emg_mean_3);
%      emg_mean_mean_4(j,:)=mean(emg_mean_4);
%      emg_mean_mean_5(j,:)=mean(emg_mean_5);
%      emg_mean_mean_6(j,:)=mean(emg_mean_6);
%      emg_mean_mean_7(j,:)=mean(emg_mean_7);
%      emg_mean_mean_8(j,:)=mean(emg_mean_8);
%
%
%      tempdataFf=[mean(ff_data_mean_x)'
mean(ff_data_mean_y)' mean(ff_data_mean_z)'
mean(ff_data_mean_m)'];
%      tempdataBf=[mean(bf_data_mean_x)'
mean(bf_data_mean_y)' mean(bf_data_mean_z)'
mean(bf_data_mean_m)'];
```

```
%      tempEmg=[mean(emg_mean_1)' mean(emg_mean_2)'
mean(emg_mean_3)' mean(emg_mean_4)' mean(emg_mean_5)'
mean(emg_mean_6)' mean(emg_mean_7)' mean(emg_mean_8)'];
%
%
%      if i==1 %cross punch
%
%          % PHASE DEFINITIONS
%          % PHASE 1
%          %   Start = 10% drop from the max of the y-axis
front foot prior to impact (before phase 2)
%          %   End   = Minimum of y-axis front foot prior to
impact
%          % PHASE 2
%          %   Start = Minimum of the y-axis front foot
prior to impact
%          %   End   = Impact start as defined in Seth's
excel document
%          % PHASE 3 (IMPACT)
%          %   Start = Impact start as defined in Seth's
excel document
%          %   End   = Impact start plus duration as defined
in Seth's excel document
%
%
[cross_pTwoMin,pos]=min(tempdataFf(phase2_search_start:phas
e2_search_end,2));
%          phase_two=timeSeries(pos+phase2_search_start);
%
%
[cross_pOneMax,pos2]=max(tempdataFf(phase1_search_start:pos
+phase1_search_end,2));
%
phase_ones=find(tempdataFf(phase1_search_start+pos2:pos+pha
se1_search_start,2) <= cross_pTwoMin+(abs(cross_pOneMax-
cross_pTwoMin)*0.9));
%
phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);
%          temp_data=[tempdataFf tempdataBf];
%
%
phase1_data=temp_data(phase_one(1)+phase1_search_start+pos2
:pos+phase1_search_end,:);
%
phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
%          phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(1).time.duration,:);
%      end
%      if i==2 %jab punch
%
```

```
%          % PHASE DEFINITIONS
%          % PHASE 1
%          %   Start = 10% drop from the max of the z-axis
back foot prior to impact (before phase 2)
%          %   End   = Minimum of z-axis back foot prior to
impact
%          % PHASE 2
%          %   Start = Minimum of the z-axis back foot prior
to impact
%          %   End   = Impact start as defined in Seth's
excel document
%          % PHASE 3 (IMPACT)
%          %   Start = Impact start as defined in Seth's
excel document
%          %   End   = Impact start plus duration as defined
in Seth's excel document
%
%
[jab_pTwoMin,pos]=min(tempdataBf(phase2_search_start:phase2
_search_end,3));
%          phase_two=timeSeries(pos+phase2_search_start);
%          temp_data=[tempdataFf tempdataBf];
%
%
[jab_pOneMax,pos2]=max(tempdataBf(phase1_search_start:pos+p
hase1_search_end,3));
%
phase_ones=find(tempdataBf(phase1_search_start+pos2:pos+pha
se1_search_start,3) <= jab_pTwoMin+(abs(jab_pOneMax-
jab_pTwoMin)*0.9));
%
phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);
%
%
phase1_data=temp_data(phase_one(1)+phase1_search_start+pos2
:pos+phase1_search_end,:);
%
phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
%          phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);
%
%      end
%
%      if i==3 %LHook
%
%          % PHASE DEFINITIONS
%          % PHASE 1
%          %   Start = crossover in z-axis as weight goes
onto front foot
%          %   End   = cross over in y-axis
```

```
%          % PHASE 2
%          %   Start = cross over in y-axis
%          %   End   = peak in the x-axis front foot prior
to impact
%          % PHASE 3
%          %   Start = peak in the x-axis front foot prior
to impact
%          %   End   = Impact start as defined in Seth's
excel document
%          % PHASE 4 (IMPACT)
%          %   Start = Impact start as defined in Seth's
excel document
%          %   End   = Impact start plus duration as defined
in Seth's excel document
%
%
[lhook_pThreeMax,pos]=max(tempdataFf(1200:1500,1))
%          if pos>=290
%
[lhook_pThreeMax,pos]=max(tempdataFf(1300:1450,1))
%              phase_three=timeSeries(pos+1300);
%          else
%              phase_three=timeSeries(pos+1200);
%          end
%
%
%
[lhook_pTwoMin,pos2]=min(abs(tempdataFf(800:pos+1200,2)-
tempdataBf(800:pos+1200,2)));
%          phase_two=timeSeries(pos2+800);
%
%          [lhook_pOne,temp_pos]=max([tempdataFf(pos2+750,3)
tempdataBf(pos2+750,3)]);
%          pos1=0;
%          if temp_pos==1 %Front foot is higher
%              for count=pos2+750:-1:1
%                  if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
%                      pos1=count;
%                  end
%              end
%          else
%              for count=pos2+750:-1:1
%                  if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
%                      pos1=count;
%                  end
%              end
%          end
%          if pos1 ==0
%              [mag,pos1]=min(abs(tempdataFf(1:pos2+750,3)-
tempdataBf(1:pos2+750,3)));
%          end
```

```
%           phase_one=timeSeries(pos1);
%
%
%           temp_data=[tempdataFf tempdataBf];
%
%           phase1_data=temp_data(pos1:pos2+800,:);
%           phase2_data=temp_data(pos2+800:pos+1200,:);
%           phase3_data=temp_data(pos+1200:plotOffset-
windowOffset,:);
%           phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);
%       end
%
%       if i==4 %RHook
%
%           % PHASE DEFINITIONS
%           % PHASE 1
%           %   Start = crossover in z-axis as weight goes
onto back foot
%           %   End   = 10% drop in y-axis front foot
%           % PHASE 2
%           %   Start = 10% drop in y-axis front foot
%           %   End   = minimum in y-axis front foot
%           % PHASE 3
%           %   Start = minimum in y-axis front foot
%           %   End   = Impact start as defined in Seth's
excel document
%           % PHASE 4 (IMPACT)
%           %   Start = Impact start as defined in Seth's
excel document
%           %   End   = Impact start plus duration as defined
in Seth's excel document
%
%
%
[rhook_pThreeMin,pos]=min(tempdataFf(1000:1500,2));
%           phase_three=timeSeries(pos+1000);
%
%
[rhook_pTwoMax,pos2]=max(tempdataFf(1150:pos+1000,2));
%           phase_twos=find(tempdataFf(1150+pos2:pos+1150,2)
<= rhook_pThreeMin+(abs(rhook_pTwoMax-
rhook_pThreeMin)*0.9));
%           phase_two=timeSeries(phase_twos(1)+1150+pos2);
%
%
[rhook_pOne,temp_pos]=max([tempdataFf(pos2+1150,3)
tempdataBf(pos2+1150,3)]);
%           pos1=0;
%           if temp_pos==1 %Front foot is higher
%               for count=phase_twos(1)+1150+pos2:-1:1
```

```
%                 if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
%                     pos1=count;
%                 end
%             end
%         else
%             for count=phase_twos(1)+1150+pos2:-1:1
%                 if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
%                     pos1=count;
%                 end
%             end
%         end
%         if pos1 ==0
%
[mag,pos1]=min(abs(tempdataFf(phase_twos(1)+1150+pos2,3)-
tempdataBf(phase_twos(1)+1150+pos2,3)));
%         end
%         phase_one=timeSeries(pos1);
%
%
%         temp_data=[tempdataFf tempdataBf];
%
%
phase1_data=temp_data(pos1:phase_twos(1)+1150+pos2,:);
%
phase2_data=temp_data(phase_twos(1)+1150+pos2:pos+1000,:);
%         phase3_data=temp_data(pos+1000:plotOffset-
windowOffset,:);
%         phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);
%
%     end
%
%     figure();
%
%     bx(1)=subplot(2,2,1);
%     plot(timeSeries,tempEmg(:,1),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_1)+std(emg_mean_1),':b')
%     plot(timeSeries,mean(emg_mean_1)-
std(emg_mean_1),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
```

```
%
%     %         title(['participant: ' num2str(j) '  Punch
Type: ' punchType{i} '  Punch Number: '
num2str(n)],'FontSize', 20);
%     ylabel('EMG 1');
%
%     bx(1)=subplot(2,2,2);
%     plot(timeSeries,tempEmg(:,2),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_2)+std(emg_mean_2),':b')
%     plot(timeSeries,mean(emg_mean_2)-
std(emg_mean_2),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%
%     ylabel('EMG 2');
%
%     bx(1)=subplot(2,2,3);
%     plot(timeSeries,tempEmg(:,3),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_3)+std(emg_mean_3),':b')
%     plot(timeSeries,mean(emg_mean_3)-
std(emg_mean_3),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%     ylabel('EMG 3');
%
%     bx(1)=subplot(2,2,4);
%     plot(timeSeries,tempEmg(:,4),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_4)+std(emg_mean_4),':b')
%     plot(timeSeries,mean(emg_mean_4)-
std(emg_mean_4),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
```

```
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%     ylabel('EMG 4');
%
%
%     figure();
%
%     bx(1)=subplot(2,2,1);
%     plot(timeSeries,tempEmg(:,5),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_5)+std(emg_mean_5),':b')
%     plot(timeSeries,mean(emg_mean_5)-
std(emg_mean_5),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%
%     %          title(['participant: ' num2str(j) '  Punch
Type: ' punchType{i} '  Punch Number: '
num2str(n)],'FontSize', 20);
%     ylabel('EMG 5');
%
%     bx(1)=subplot(2,2,2);
%     plot(timeSeries,tempEmg(:,6),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_6)+std(emg_mean_6),':b')
%     plot(timeSeries,mean(emg_mean_6)-
std(emg_mean_6),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%
%     ylabel('EMG 6');
%
%     bx(1)=subplot(2,2,3);
```

```
%     plot(timeSeries,tempEmg(:,7),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_7)+std(emg_mean_7),':b')
%     plot(timeSeries,mean(emg_mean_7)-
std(emg_mean_7),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%     ylabel('EMG 7');
%
%     bx(1)=subplot(2,2,4);
%     plot(timeSeries,tempEmg(:,8),'b','LineWidth',2);hold
on;
%
plot(timeSeries,mean(emg_mean_8)+std(emg_mean_8),':b')
%     plot(timeSeries,mean(emg_mean_8)-
std(emg_mean_8),':b')
%
%     line([phase_two phase_two],ylim);
%     line([phase_one phase_one],ylim);
%     line([data.pID(j).type(i).punch(1).time.duration
data.pID(j).type(i).punch(1).time.duration],ylim);
%
%     if i==3 || i==4
%         line([phase_three phase_three],ylim);
%     end
%     ylabel('EMG 8');
% end


function [data] = mvic_load(playerNo,data,p_num)
% Create Filters
[b1,a1] = butter(4,[0.02 0.9],'bandpass');
[b2,a2] = butter(4,0.006,'low');

% Data stored in following order
% ABS_R, ABS_L, FEM_R, FEM_L, LAT_R, LAT_L, TRI_R, TRI_L
mvic.data=[];

%% ABS - RIGHT & LEFT

fid = fopen('Abs01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);
```

```
for i=1:length(position)
    if position{i}>=1
        out=i;
    end
end

temp_file=csvread('Abs01.csv',5,1);

mvic(1).data=temp_file(:,out-1);
mvic(2).data=temp_file(:,out);

%% FEM - RIGHT

fid = fopen('RecFemR01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);

for i=1:length(position)
    if position{i}>=1
        out=i;
    end
end

temp_file=csvread('RecFemR01.csv',5,1);

mvic(3).data=temp_file(:,out+1);

%% FEM - LEFT

fid = fopen('RecFemL01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);

for i=1:length(position)
    if position{i}>=1
        out=i;
    end
end

temp_file=csvread('RecFemL01.csv',5,1);

mvic(4).data=temp_file(:,out+2);

%% LAT - RIGHT & LEFT

fid = fopen('Lats01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
```

```
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);

for i=1:length(position)
    if position{i}>=1
        out=i;
    end
end

temp_file=csvread('Lats01.csv',5,1);

if p_num==10 || p_num==11
    mvic(5).data=temp_file(:,out+5);
else
    mvic(5).data=temp_file(:,out+3);
end

mvic(6).data=temp_file(:,out+4);

%% TRI - RIGHT

fid = fopen('TriR01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);

for i=1:length(position)
    if position{i}>=1
        out=i;
    end
end

temp_file=csvread('TriR01.csv',5,1);

if p_num==10 || p_num==11
    disp('Grabbing channel 8 for TRI_R')
    mvic(7).data=temp_file(:,out+6);
else
    mvic(7).data=temp_file(:,out+5);
end

%% TRI - LEFT

fid = fopen('TriL01.csv');
HDRS = textscan(fid,'%s','delimiter','\n');
test = textscan(HDRS{1,1}{3,1},'%s','delimiter',',');
position=regexpi(test{:},'Analog EMG - Voltage');
fclose(fid);

for i=1:length(position)
    if position{i}>=1
        out=i;
```

```
    end
end

temp_file=csvread('TriL01.csv',5,1);

mvic(8).data=temp_file(:,out+6);



%% Calculate MVIC data
figure();
for i=1:8
    hold on;
plot(mvic(i).data);
end

figure();
for i=1:8

    dataOut = filtfilt(b1,a1,mvic(i).data);
    dataOut = abs(dataOut);
    dataOut2 = filtfilt(b2,a2,dataOut);
    mvic_out(i)=max(dataOut2);

    hold on;
    plot(dataOut2);
end



lear all; close all; clc;

%plotting stuff
load('data6.mat');
fig_count=1;
punchType={'Cross','Jab','LHook','RHook'};
%-------------------------------%

fID=fopen('grf_text3.txt','w');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
%                       |--- Cross (1) --- punch (1-7)
%                       |
%                       |--- Jab   (2) --- punch (1-7)
% participant (1-11) ---|
%                       |--- LHook (3) --- punch (1-7)
%                       |
%                       |--- RHook (4) --- punch (1-7)
%
%
% each punch contains the following information:
%
```

```
% Data                        Matrix size        Details
Abreviation
% -------------------        -----------        -------
-----------
% acceleration data          3 x n              (x,y,z)
acc
% acceleration mag           1 x n              (m)
accM
% ground reaction front      3 x n              (x,y,z)
grfF
% ground reaction front mag 1 x n               (m)
grfFM
% ground reaction back       3 x n              (x,y,z)
grfB
% ground reaction back mag   1 x n              (m)
grfBM
% analog emg                 8 x n              (1,...,8)
emg
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%

%% Plot GRF overlay and acc mean and std for each punch
type
windowSize=2000;
windowOffset=-500;
timeSeries=(-
windowSize/2)+windowOffset:(windowSize/2)+windowOffset;
plotOffset=(windowSize/2);


phase2_search_start=1000;
phase2_search_end=1500;
phase1_search_start=1150;
phase1_search_end=1000;

colorSeries=['r' 'g' 'b' 'k'];

[b1,a1] = butter(4,0.05,'low');
[b2,a2] = butter(4,0.0005,'high');
punch_no=1;
for i=3%:4                    %loop for the four punchs
    clear tempdata;
    for j=1:10          %loop for all participants
        tempdataF=[];
        tempdataB=[];
        c=1;
        for n=3:7

start=round(data.pID(j).type(i).punch(n).time.start);

punch_end=round(data.pID(j).type(i).punch(n).time.end);
```

```
tempdataF=data.pID(j).type(i).punch(n).grfF(start-
plotOffset+windowOffset:start+plotOffset+windowOffset,:);

tempdataB=data.pID(j).type(i).punch(n).grfB(start-
plotOffset+windowOffset:start+plotOffset+windowOffset,:);
            tempdataF=[tempdataF
sqrt(tempdataF(:,1).^2+tempdataF(:,2).^2+tempdataF(:,3).^2)
];
            tempdataB=[tempdataB
sqrt(tempdataB(:,1).^2+tempdataB(:,2).^2+tempdataB(:,3).^2)
];

            tempdataFf = filtfilt(b1,a1,tempdataF);
            tempdataBf = filtfilt(b1,a1,tempdataB);


raw_data.punch_type(i).pID(j).punch_no(n).ff=tempdataFf;

raw_data.punch_type(i).pID(j).punch_no(n).bf=tempdataBf;

            if i==1 %cross punch

                % PHASE DEFINITIONS
                % PHASE 1
                %   Start = 10% drop from the max of the y-
axis front foot prior to impact (before phase 2)
                %   End   = Minimum of y-axis front foot
prior to impact
                % PHASE 2
                %   Start = Minimum of the y-axis front
foot prior to impact
                %   End   = Impact start as defined in
Seth's excel document
                % PHASE 3 (IMPACT)
                %   Start = Impact start as defined in
Seth's excel document
                %   End   = Impact start plus duration as
defined in Seth's excel document


[cross_pTwoMin,pos]=min(tempdataFf(phase2_search_start:phas
e2_search_end,2));

phase_two=timeSeries(pos+phase2_search_start);


[cross_pOneMax,pos2]=max(tempdataFf(phase1_search_start:pos
+phase1_search_end,2));

phase_ones=find(tempdataFf(phase1_search_start+pos2:pos+pha
se1_search_start,2) <= cross_pTwoMin+(abs(cross_pOneMax-
cross_pTwoMin)*0.9));
```

```
phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);
                temp_data=[tempdataFf tempdataBf];


phase1_data=temp_data(phase_one(1)+phase1_search_start+pos2
:pos+phase1_search_end,:);

phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
                phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);

                % PHASE 1


punch(punch_no).phase(1).max=max(phase1_data);

punch(punch_no).phase(1).min=min(phase1_data);

punch(punch_no).phase(1).mean=mean(phase1_data);


punch(punch_no).phase(1).rfdmax=max(diff(phase1_data))*1000
;

punch(punch_no).phase(1).rfdmin=min(diff(phase1_data))*1000
;

                punch(punch_no).phase(1).maxy_div_xz=
[punch(punch_no).phase(1).max(2)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(6)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meany_div_xz=[punch(punch_no).phas
e(1).mean(2)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(6)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxx_div_yz=
[punch(punch_no).phase(1).max(1)/(punch(punch_no).phase(1).
mean(2)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(5)/(punch(punch_no).phase(1).m
ean(6)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meanx_div_yz=[punch(punch_no).phas
e(1).mean(1)/(punch(punch_no).phase(1).mean(2)+punch(punch_
no).phase(1).mean(3))
```

```
punch(punch_no).phase(1).mean(5)/(punch(punch_no).phase(1).
mean(6)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxz_div_xy=
[punch(punch_no).phase(1).max(3)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(2))
punch(punch_no).phase(1).max(7)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(6))];

punch(punch_no).phase(1).meanz_div_xy=[punch(punch_no).phas
e(1).mean(3)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(2))
punch(punch_no).phase(1).mean(7)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(6))];

                punch(punch_no).phase(1).maxy_div_z=
[punch(punch_no).phase(1).max(2)/punch(punch_no).phase(1).m
ean(3)
punch(punch_no).phase(1).max(6)/punch(punch_no).phase(1).me
an(7)];

punch(punch_no).phase(1).meany_div_z=[punch(punch_no).phase
(1).mean(2)/punch(punch_no).phase(1).mean(3)
punch(punch_no).phase(1).mean(6)/punch(punch_no).phase(1).m
ean(7)];

                % PHASE 2

punch(punch_no).phase(2).max=max(phase2_data);

punch(punch_no).phase(2).min=min(phase2_data);

punch(punch_no).phase(2).mean=mean(phase2_data);


punch(punch_no).phase(2).rfdmax=max(diff(phase2_data))*1000
;

punch(punch_no).phase(2).rfdmin=min(diff(phase2_data))*1000
;

                punch(punch_no).phase(2).maxy_div_xz=
[punch(punch_no).phase(2).max(2)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(6)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meany_div_xz=[punch(punch_no).phas
e(2).mean(2)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(6)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(7))];
```

```
                punch(punch_no).phase(2).maxx_div_yz=
[punch(punch_no).phase(2).max(1)/(punch(punch_no).phase(2).
mean(2)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(5)/(punch(punch_no).phase(2).m
ean(6)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meanx_div_yz=[punch(punch_no).phas
e(2).mean(1)/(punch(punch_no).phase(2).mean(2)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(5)/(punch(punch_no).phase(2).
mean(6)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxz_div_xy=
[punch(punch_no).phase(2).max(3)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(2))
punch(punch_no).phase(2).max(7)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(6))];

punch(punch_no).phase(2).meanz_div_xy=[punch(punch_no).phas
e(2).mean(3)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(2))
punch(punch_no).phase(2).mean(7)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(6))];

                punch(punch_no).phase(2).maxy_div_z=
[punch(punch_no).phase(2).max(2)/punch(punch_no).phase(2).m
ean(3)
punch(punch_no).phase(2).max(6)/punch(punch_no).phase(2).me
an(7)];

punch(punch_no).phase(2).meany_div_z=[punch(punch_no).phase
(2).mean(2)/punch(punch_no).phase(2).mean(3)
punch(punch_no).phase(2).mean(6)/punch(punch_no).phase(2).m
ean(7)];

                % PHASE 3 IMPACT

punch(punch_no).phase(3).max=max(phase3_data);

punch(punch_no).phase(3).min=min(phase3_data);

punch(punch_no).phase(3).mean=mean(phase3_data);


punch(punch_no).phase(3).rfdmax=max(diff(phase3_data))*1000
;

punch(punch_no).phase(3).rfdmin=min(diff(phase3_data))*1000
;

                punch(punch_no).phase(3).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(3))
```

```
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meany_div_xz=[punch(punch_no).phas
e(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).
mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).m
ean(6)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];

punch(punch_no).phase(3).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(3).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(3).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];

            end

            if i==2 %jab punch

                % PHASE DEFINITIONS
                % PHASE 1
                %   Start = 10% drop from the max of the z-
axis back foot prior to impact (before phase 2)
```

```
                % End   = Minimum of z-axis back foot
prior to impact
                % PHASE 2
                % Start = Minimum of the z-axis back foot
prior to impact
                % End   = Impact start as defined in
Seth's excel document
                % PHASE 3 (IMPACT)
                % Start = Impact start as defined in
Seth's excel document
                % End   = Impact start plus duration as
defined in Seth's excel document


[jab_pTwoMin,pos]=min(tempdataBf(phase2_search_start:phase2
_search_end,3));

phase_two=timeSeries(pos+phase2_search_start);
                temp_data=[tempdataFf tempdataBf];


[jab_pOneMax,pos2]=max(tempdataBf(phase1_search_start:pos+p
hase1_search_end,3));

phase_ones=find(tempdataBf(phase1_search_start+pos2:pos+pha
se1_search_start,3) <= jab_pTwoMin+(abs(jab_pOneMax-
jab_pTwoMin)*0.9));

phase_one=timeSeries(phase_ones(1)+phase1_search_start+pos2
);


phase1_data=temp_data(phase_one(1)+phase1_search_start+pos2
:pos+phase1_search_end,:);

phase2_data=temp_data(pos+phase2_search_start:phase2_search
_end,:);
                phase3_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);

                % PHASE 1

punch(punch_no).phase(1).max=max(phase1_data);

punch(punch_no).phase(1).min=min(phase1_data);

punch(punch_no).phase(1).mean=mean(phase1_data);


punch(punch_no).phase(1).rfdmax=max(diff(phase1_data))*1000
;
```

```
punch(punch_no).phase(1).rfdmin=min(diff(phase1_data))*1000
;

                punch(punch_no).phase(1).maxy_div_xz=
[punch(punch_no).phase(1).max(2)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(6)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meany_div_xz=[punch(punch_no).phas
e(1).mean(2)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(6)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxx_div_yz=
[punch(punch_no).phase(1).max(1)/(punch(punch_no).phase(1).
mean(2)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(5)/(punch(punch_no).phase(1).m
ean(6)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meanx_div_yz=[punch(punch_no).phas
e(1).mean(1)/(punch(punch_no).phase(1).mean(2)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(5)/(punch(punch_no).phase(1).
mean(6)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxz_div_xy=
[punch(punch_no).phase(1).max(3)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(2))
punch(punch_no).phase(1).max(7)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(6))];

punch(punch_no).phase(1).meanz_div_xy=[punch(punch_no).phas
e(1).mean(3)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(2))
punch(punch_no).phase(1).mean(7)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(6))];

                punch(punch_no).phase(1).maxy_div_z=
[punch(punch_no).phase(1).max(2)/punch(punch_no).phase(1).m
ean(3)
punch(punch_no).phase(1).max(6)/punch(punch_no).phase(1).me
an(7)];

punch(punch_no).phase(1).meany_div_z=[punch(punch_no).phase
(1).mean(2)/punch(punch_no).phase(1).mean(3)
punch(punch_no).phase(1).mean(6)/punch(punch_no).phase(1).m
ean(7)];


                % PHASE 2
```

```
punch(punch_no).phase(2).max=max(phase2_data);

punch(punch_no).phase(2).min=min(phase2_data);

punch(punch_no).phase(2).mean=mean(phase2_data);


punch(punch_no).phase(2).rfdmax=max(diff(phase2_data))*1000
;

punch(punch_no).phase(2).rfdmin=min(diff(phase2_data))*1000
;

                punch(punch_no).phase(2).maxy_div_xz=
[punch(punch_no).phase(2).max(2)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(6)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meany_div_xz=[punch(punch_no).phas
e(2).mean(2)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(6)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxx_div_yz=
[punch(punch_no).phase(2).max(1)/(punch(punch_no).phase(2).
mean(2)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(5)/(punch(punch_no).phase(2).m
ean(6)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meanx_div_yz=[punch(punch_no).phas
e(2).mean(1)/(punch(punch_no).phase(2).mean(2)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(5)/(punch(punch_no).phase(2).
mean(6)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxz_div_xy=
[punch(punch_no).phase(2).max(3)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(2))
punch(punch_no).phase(2).max(7)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(6))];

punch(punch_no).phase(2).meanz_div_xy=[punch(punch_no).phas
e(2).mean(3)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(2))
punch(punch_no).phase(2).mean(7)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(6))];

                punch(punch_no).phase(2).maxy_div_z=
[punch(punch_no).phase(2).max(2)/punch(punch_no).phase(2).m
ean(3)
```

```
punch(punch_no).phase(2).max(6)/punch(punch_no).phase(2).me
an(7)];

punch(punch_no).phase(2).meany_div_z=[punch(punch_no).phase
(2).mean(2)/punch(punch_no).phase(2).mean(3)
punch(punch_no).phase(2).mean(6)/punch(punch_no).phase(2).m
ean(7)];


                % PHASE 3 IMPACT

punch(punch_no).phase(3).max=max(phase3_data);

punch(punch_no).phase(3).min=min(phase3_data);

punch(punch_no).phase(3).mean=mean(phase3_data);


punch(punch_no).phase(3).rfdmax=max(diff(phase3_data))*1000
;

punch(punch_no).phase(3).rfdmin=min(diff(phase3_data))*1000
;

                punch(punch_no).phase(3).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meany_div_xz=[punch(punch_no).phas
e(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).
mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).m
ean(6)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];
```

```
punch(punch_no).phase(3).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(3).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(3).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];
            end

            if i==3 %LHook

                % PHASE DEFINITIONS
                % PHASE 1
                %   Start = crossover in z-axis as weight
goes onto front foot
                %   End   = cross over in y-axis
                % PHASE 2
                %   Start = cross over in y-axis
                %   End   = peak in the x-axis front foot
prior to impact
                % PHASE 3
                %   Start = peak in the x-axis front foot
prior to impact
                %   End   = Impact start as defined in
Seth's excel document
                % PHASE 4 (IMPACT)
                %   Start = Impact start as defined in
Seth's excel document
                %   End   = Impact start plus duration as
defined in Seth's excel document


[lhook_pThreeMax,pos]=max(tempdataFf(1200:1500,1))
                if pos>=290

[lhook_pThreeMax,pos]=max(tempdataFf(1300:1450,1))
                    phase_three=timeSeries(pos+1300);
                else
                    phase_three=timeSeries(pos+1200);
                end
```

```
[lhook_pTwoMin,pos2]=min(abs(tempdataFf(800:pos+1200,2)-
tempdataBf(800:pos+1200,2)));
                phase_two=timeSeries(pos2+800);


[lhook_pOne,temp_pos]=max([tempdataFf(pos2+750,3)
tempdataBf(pos2+750,3)]);
                pos1=0;
                if temp_pos==1 %Front foot is higher
                    for count=pos2+750:-1:1
                        if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
                            pos1=count;
                        end
                    end
                else
                    for count=pos2+750:-1:1
                        if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
                            pos1=count;
                        end
                    end
                end
                if pos1 ==0

[mag,pos1]=min(abs(tempdataFf(1:pos2+750,3)-
tempdataBf(1:pos2+750,3)));
                end
                phase_one=timeSeries(pos1);


                temp_data=[tempdataFf tempdataBf];

                phase1_data=temp_data(pos1:pos2+800,:);
                phase2_data=temp_data(pos2+800:pos+1200,:);
                phase3_data=temp_data(pos+1200:plotOffset-
windowOffset,:);
                phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);



                % PHASE 1

punch(punch_no).phase(1).max=max(phase1_data);

punch(punch_no).phase(1).min=min(phase1_data);

punch(punch_no).phase(1).mean=mean(phase1_data);
```

```
punch(punch_no).phase(1).rfdmax=max(diff(phase1_data))*1000
;

punch(punch_no).phase(1).rfdmin=min(diff(phase1_data))*1000
;

                punch(punch_no).phase(1).maxy_div_xz=
[punch(punch_no).phase(1).max(2)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(6)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meany_div_xz=[punch(punch_no).phas
e(1).mean(2)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(6)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxx_div_yz=
[punch(punch_no).phase(1).max(1)/(punch(punch_no).phase(1).
mean(2)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(5)/(punch(punch_no).phase(1).m
ean(6)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meanx_div_yz=[punch(punch_no).phas
e(1).mean(1)/(punch(punch_no).phase(1).mean(2)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(5)/(punch(punch_no).phase(1).
mean(6)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxz_div_xy=
[punch(punch_no).phase(1).max(3)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(2))
punch(punch_no).phase(1).max(7)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(6))];

punch(punch_no).phase(1).meanz_div_xy=[punch(punch_no).phas
e(1).mean(3)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(2))
punch(punch_no).phase(1).mean(7)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(6))];

                punch(punch_no).phase(1).maxy_div_z=
[punch(punch_no).phase(1).max(2)/punch(punch_no).phase(1).m
ean(3)
punch(punch_no).phase(1).max(6)/punch(punch_no).phase(1).me
an(7)];

punch(punch_no).phase(1).meany_div_z=[punch(punch_no).phase
(1).mean(2)/punch(punch_no).phase(1).mean(3)
punch(punch_no).phase(1).mean(6)/punch(punch_no).phase(1).m
ean(7)];
```

```
                % PHASE 2

punch(punch_no).phase(2).max=max(phase2_data);

punch(punch_no).phase(2).min=min(phase2_data);

punch(punch_no).phase(2).mean=mean(phase2_data);


punch(punch_no).phase(2).rfdmax=max(diff(phase2_data))*1000
;

punch(punch_no).phase(2).rfdmin=min(diff(phase2_data))*1000
;

                punch(punch_no).phase(2).maxy_div_xz=
[punch(punch_no).phase(2).max(2)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(6)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meany_div_xz=[punch(punch_no).phas
e(2).mean(2)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(6)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxx_div_yz=
[punch(punch_no).phase(2).max(1)/(punch(punch_no).phase(2).
mean(2)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(5)/(punch(punch_no).phase(2).m
ean(6)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meanx_div_yz=[punch(punch_no).phas
e(2).mean(1)/(punch(punch_no).phase(2).mean(2)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(5)/(punch(punch_no).phase(2).
mean(6)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxz_div_xy=
[punch(punch_no).phase(2).max(3)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(2))
punch(punch_no).phase(2).max(7)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(6))];

punch(punch_no).phase(2).meanz_div_xy=[punch(punch_no).phas
e(2).mean(3)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(2))
punch(punch_no).phase(2).mean(7)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(6))];
```

```
                punch(punch_no).phase(2).maxy_div_z=
[punch(punch_no).phase(2).max(2)/punch(punch_no).phase(2).m
ean(3)
punch(punch_no).phase(2).max(6)/punch(punch_no).phase(2).me
an(7)];

punch(punch_no).phase(2).meany_div_z=[punch(punch_no).phase
(2).mean(2)/punch(punch_no).phase(2).mean(3)
punch(punch_no).phase(2).mean(6)/punch(punch_no).phase(2).m
ean(7)];


                % PHASE 3

punch(punch_no).phase(3).max=max(phase3_data);

punch(punch_no).phase(3).min=min(phase3_data);

punch(punch_no).phase(3).mean=mean(phase3_data);


punch(punch_no).phase(3).rfdmax=max(diff(phase3_data))*1000
;

punch(punch_no).phase(3).rfdmin=min(diff(phase3_data))*1000
;

                punch(punch_no).phase(3).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meany_div_xz=[punch(punch_no).phas
e(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).
mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).m
ean(6)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
```

```
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];

punch(punch_no).phase(3).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(3).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(3).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];

                % PHASE 4 IMPACT

punch(punch_no).phase(4).max=max(phase4_data);

punch(punch_no).phase(4).min=min(phase4_data);

punch(punch_no).phase(4).mean=mean(phase4_data);


punch(punch_no).phase(4).rfdmax=max(diff(phase4_data))*1000
;

punch(punch_no).phase(4).rfdmin=min(diff(phase4_data))*1000
;

                punch(punch_no).phase(4).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(4).meany_div_xz=[punch(punch_no).phas
e(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(4).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).
mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).m
ean(6)+punch(punch_no).phase(3).mean(7))];
```

```
punch(punch_no).phase(4).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(4).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];

punch(punch_no).phase(4).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(4).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(4).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];

            end
            if i==4 %RHook

                % PHASE DEFINITIONS
                % PHASE 1
                %   Start = crossover in z-axis as weight
goes onto back foot
                %   End   = 10% drop in y-axis front foot
                % PHASE 2
                %   Start = 10% drop in y-axis front foot
                %   End   = minimum in y-axis front foot
                % PHASE 3
                %   Start = minimum in y-axis front foot
                %   End   = Impact start as defined in
Seth's excel document
                % PHASE 4 (IMPACT)
                %   Start = Impact start as defined in
Seth's excel document
                %   End   = Impact start plus duration as
defined in Seth's excel document
```

```
[rhook_pThreeMin,pos]=min(tempdataFf(1000:1500,2));
                phase_three=timeSeries(pos+1000);


[rhook_pTwoMax,pos2]=max(tempdataFf(1150:pos+1000,2));

phase_twos=find(tempdataFf(1150+pos2:pos+1150,2) <=
rhook_pThreeMin+(abs(rhook_pTwoMax-rhook_pThreeMin)*0.9));

phase_two=timeSeries(phase_twos(1)+1150+pos2);


[rhook_pOne,temp_pos]=max([tempdataFf(pos2+1150,3)
tempdataBf(pos2+1150,3)]);
                pos1=0;
                if temp_pos==1 %Front foot is higher
                    for count=phase_twos(1)+1150+pos2:-1:1
                        if
tempdataBf(count,3)>tempdataFf(count,3) & pos1==0
                            pos1=count;
                        end
                    end
                else
                    for count=phase_twos(1)+1150+pos2:-1:1
                        if
tempdataBf(count,3)<tempdataFf(count,3) & pos1==0
                            pos1=count;
                        end
                    end
                end
                if pos1 ==0

[mag,pos1]=min(abs(tempdataFf(phase_twos(1)+1150+pos2,3)-
tempdataBf(phase_twos(1)+1150+pos2,3)));
                end
                phase_one=timeSeries(pos1);


                temp_data=[tempdataFf tempdataBf];


phase1_data=temp_data(pos1:phase_twos(1)+1150+pos2,:);

phase2_data=temp_data(phase_twos(1)+1150+pos2:pos+1000,:);
                phase3_data=temp_data(pos+1000:plotOffset-
windowOffset,:);
                phase4_data=temp_data(plotOffset-
windowOffset:plotOffset-
windowOffset+data.pID(j).type(i).punch(n).time.duration,:);
```

```
                % PHASE 1

punch(punch_no).phase(1).max=max(phase1_data);

punch(punch_no).phase(1).min=min(phase1_data);

punch(punch_no).phase(1).mean=mean(phase1_data);


punch(punch_no).phase(1).rfdmax=max(diff(phase1_data))*1000
;

punch(punch_no).phase(1).rfdmin=min(diff(phase1_data))*1000
;

                punch(punch_no).phase(1).maxy_div_xz=
[punch(punch_no).phase(1).max(2)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(6)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meany_div_xz=[punch(punch_no).phas
e(1).mean(2)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(6)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxx_div_yz=
[punch(punch_no).phase(1).max(1)/(punch(punch_no).phase(1).
mean(2)+punch(punch_no).phase(1).mean(3))
punch(punch_no).phase(1).max(5)/(punch(punch_no).phase(1).m
ean(6)+punch(punch_no).phase(1).mean(7))];

punch(punch_no).phase(1).meanx_div_yz=[punch(punch_no).phas
e(1).mean(1)/(punch(punch_no).phase(1).mean(2)+punch(punch_
no).phase(1).mean(3))
punch(punch_no).phase(1).mean(5)/(punch(punch_no).phase(1).
mean(6)+punch(punch_no).phase(1).mean(7))];

                punch(punch_no).phase(1).maxz_div_xy=
[punch(punch_no).phase(1).max(3)/(punch(punch_no).phase(1).
mean(1)+punch(punch_no).phase(1).mean(2))
punch(punch_no).phase(1).max(7)/(punch(punch_no).phase(1).m
ean(5)+punch(punch_no).phase(1).mean(6))];

punch(punch_no).phase(1).meanz_div_xy=[punch(punch_no).phas
e(1).mean(3)/(punch(punch_no).phase(1).mean(1)+punch(punch_
no).phase(1).mean(2))
punch(punch_no).phase(1).mean(7)/(punch(punch_no).phase(1).
mean(5)+punch(punch_no).phase(1).mean(6))];

                punch(punch_no).phase(1).maxy_div_z=
[punch(punch_no).phase(1).max(2)/punch(punch_no).phase(1).m
```

```
ean(3)
punch(punch_no).phase(1).max(6)/punch(punch_no).phase(1).me
an(7)];

punch(punch_no).phase(1).meany_div_z=[punch(punch_no).phase
(1).mean(2)/punch(punch_no).phase(1).mean(3)
punch(punch_no).phase(1).mean(6)/punch(punch_no).phase(1).m
ean(7)];


                % PHASE 2

punch(punch_no).phase(2).max=max(phase2_data);

punch(punch_no).phase(2).min=min(phase2_data);

punch(punch_no).phase(2).mean=mean(phase2_data);


punch(punch_no).phase(2).rfdmax=max(diff(phase2_data))*1000
;

punch(punch_no).phase(2).rfdmin=min(diff(phase2_data))*1000
;

                punch(punch_no).phase(2).maxy_div_xz=
[punch(punch_no).phase(2).max(2)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(6)/(punch(punch_no).phase(2).m
ean(5)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meany_div_xz=[punch(punch_no).phas
e(2).mean(2)/(punch(punch_no).phase(2).mean(1)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(6)/(punch(punch_no).phase(2).
mean(5)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxx_div_yz=
[punch(punch_no).phase(2).max(1)/(punch(punch_no).phase(2).
mean(2)+punch(punch_no).phase(2).mean(3))
punch(punch_no).phase(2).max(5)/(punch(punch_no).phase(2).m
ean(6)+punch(punch_no).phase(2).mean(7))];

punch(punch_no).phase(2).meanx_div_yz=[punch(punch_no).phas
e(2).mean(1)/(punch(punch_no).phase(2).mean(2)+punch(punch_
no).phase(2).mean(3))
punch(punch_no).phase(2).mean(5)/(punch(punch_no).phase(2).
mean(6)+punch(punch_no).phase(2).mean(7))];

                punch(punch_no).phase(2).maxz_div_xy=
[punch(punch_no).phase(2).max(3)/(punch(punch_no).phase(2).
mean(1)+punch(punch_no).phase(2).mean(2))
```

```
punch(punch_no).phase(2).max(7)/(punch(punch_no).phase(2).mean(5)+punch(punch_no).phase(2).mean(6))];

punch(punch_no).phase(2).meanz_div_xy=[punch(punch_no).phase(2).mean(3)/(punch(punch_no).phase(2).mean(1)+punch(punch_no).phase(2).mean(2))
punch(punch_no).phase(2).mean(7)/(punch(punch_no).phase(2).mean(5)+punch(punch_no).phase(2).mean(6))];

                punch(punch_no).phase(2).maxy_div_z=
[punch(punch_no).phase(2).max(2)/punch(punch_no).phase(2).mean(3)
punch(punch_no).phase(2).max(6)/punch(punch_no).phase(2).mean(7)];

punch(punch_no).phase(2).meany_div_z=[punch(punch_no).phase(2).mean(2)/punch(punch_no).phase(2).mean(3)
punch(punch_no).phase(2).mean(6)/punch(punch_no).phase(2).mean(7)];


                % PHASE 3

punch(punch_no).phase(3).max=max(phase3_data);

punch(punch_no).phase(3).min=min(phase3_data);

punch(punch_no).phase(3).mean=mean(phase3_data);


punch(punch_no).phase(3).rfdmax=max(diff(phase3_data))*1000;

punch(punch_no).phase(3).rfdmin=min(diff(phase3_data))*1000;

                punch(punch_no).phase(3).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).mean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(3).meany_div_xz=[punch(punch_no).phase(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).mean(6)+punch(punch_no).phase(3).mean(7))];
```

```
punch(punch_no).phase(3).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(3).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];

punch(punch_no).phase(3).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(3).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(3).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];

                % PHASE 4 IMPACT

punch(punch_no).phase(4).max=max(phase4_data);

punch(punch_no).phase(4).min=min(phase4_data);

punch(punch_no).phase(4).mean=mean(phase4_data);


punch(punch_no).phase(4).rfdmax=max(diff(phase4_data))*1000
;

punch(punch_no).phase(4).rfdmin=min(diff(phase4_data))*1000
;

                punch(punch_no).phase(4).maxy_div_xz=
[punch(punch_no).phase(3).max(2)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(6)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(4).meany_div_xz=[punch(punch_no).phas
e(3).mean(2)/(punch(punch_no).phase(3).mean(1)+punch(punch_
```

```
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(6)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(4).maxx_div_yz=
[punch(punch_no).phase(3).max(1)/(punch(punch_no).phase(3).
mean(2)+punch(punch_no).phase(3).mean(3))
punch(punch_no).phase(3).max(5)/(punch(punch_no).phase(3).m
ean(6)+punch(punch_no).phase(3).mean(7))];

punch(punch_no).phase(4).meanx_div_yz=[punch(punch_no).phas
e(3).mean(1)/(punch(punch_no).phase(3).mean(2)+punch(punch_
no).phase(3).mean(3))
punch(punch_no).phase(3).mean(5)/(punch(punch_no).phase(3).
mean(6)+punch(punch_no).phase(3).mean(7))];

                punch(punch_no).phase(4).maxz_div_xy=
[punch(punch_no).phase(3).max(3)/(punch(punch_no).phase(3).
mean(1)+punch(punch_no).phase(3).mean(2))
punch(punch_no).phase(3).max(7)/(punch(punch_no).phase(3).m
ean(5)+punch(punch_no).phase(3).mean(6))];

punch(punch_no).phase(4).meanz_div_xy=[punch(punch_no).phas
e(3).mean(3)/(punch(punch_no).phase(3).mean(1)+punch(punch_
no).phase(3).mean(2))
punch(punch_no).phase(3).mean(7)/(punch(punch_no).phase(3).
mean(5)+punch(punch_no).phase(3).mean(6))];

                punch(punch_no).phase(4).maxy_div_z=
[punch(punch_no).phase(3).max(2)/punch(punch_no).phase(3).m
ean(3)
punch(punch_no).phase(3).max(6)/punch(punch_no).phase(3).me
an(7)];

punch(punch_no).phase(4).meany_div_z=[punch(punch_no).phase
(3).mean(2)/punch(punch_no).phase(3).mean(3)
punch(punch_no).phase(3).mean(6)/punch(punch_no).phase(3).m
ean(7)];


            end


            if i==3 || i==4
                p_cnt_end=4;
            else
                p_cnt_end=3;
            end


fprintf(fID,'%s,%s,%s,',num2str(i),num2str(j),num2str(n));
            for p_cnt=1:p_cnt_end
```

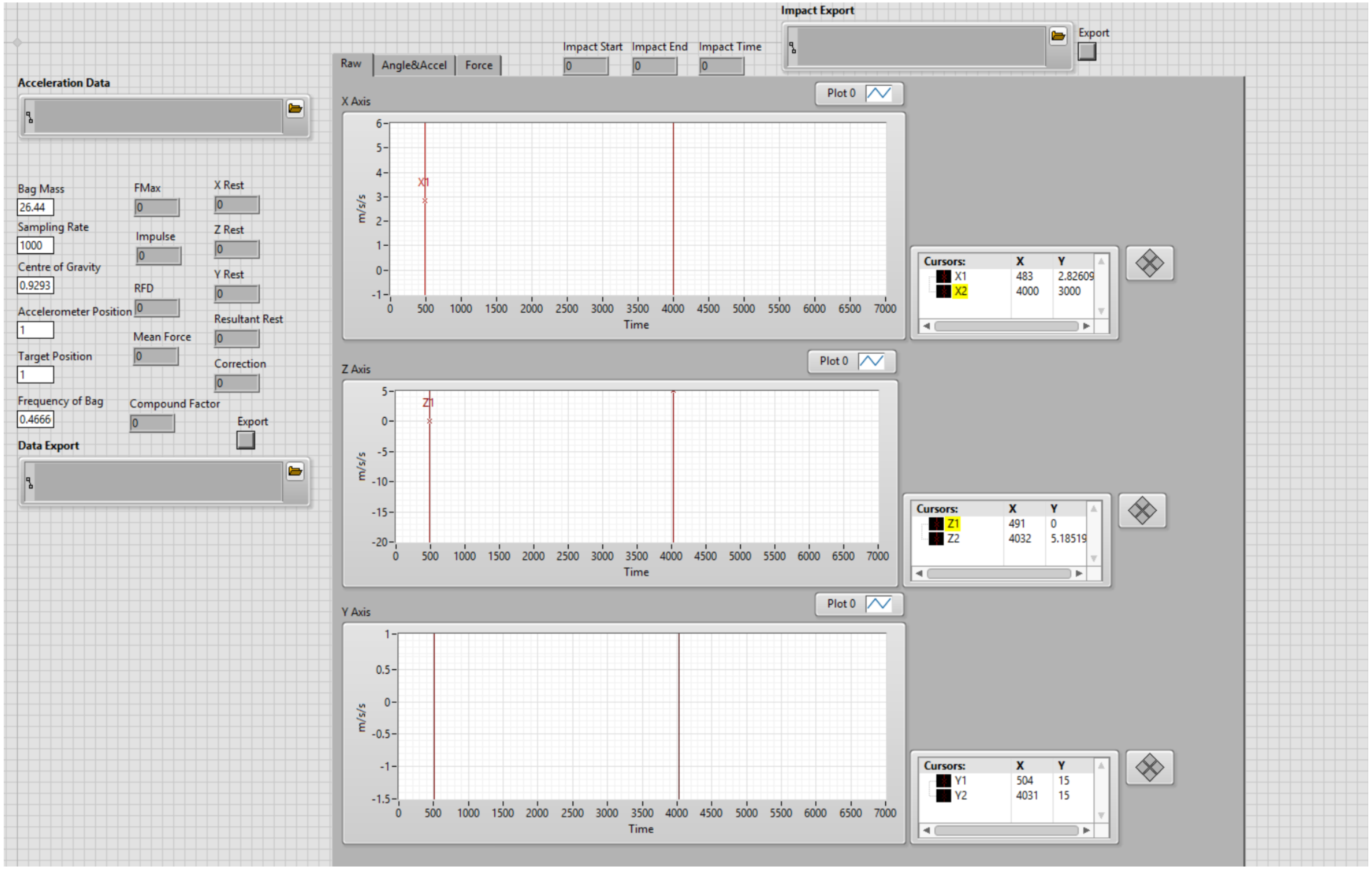
```
fprintf(fID,'%f,%f,%f,%f,%f,%f,%f,%f,',punch(punch_no).phas
e(p_cnt).max);

fprintf(fID,'%f,%f,%f,%f,%f,%f,%f,%f,',punch(punch_no).phas
e(p_cnt).min);

fprintf(fID,'%f,%f,%f,%f,%f,%f,%f,%f,',punch(punch_no).phas
e(p_cnt).mean);

fprintf(fID,'%f,%f,%f,%f,%f,%f,%f,%f,',punch(punch_no).phas
e(p_cnt).rfdmax);

fprintf(fID,'%f,%f,%f,%f,%f,%f,%f,%f,',punch(punch_no).phas
e(p_cnt).rfdmin);
            end
            fprintf(fID,'\n');

            figure(fig_count);

            bx(1)=subplot(3,1,1);

plot(timeSeries,tempdataFf(:,1),'b','LineWidth',2);hold on;

plot(timeSeries,tempdataBf(:,1),'k','LineWidth',2);

line([data.pID(j).type(i).punch(n).time.duration
data.pID(j).type(i).punch(n).time.duration],ylim);
            if i==1
                line([phase_two
phase_two],ylim,'Color','g');
                line([phase_one
phase_one],ylim,'Color','g');
            elseif i==2
                line([phase_two
phase_two],ylim,'Color','g');
                line([phase_one
phase_one],ylim,'Color','g');
            elseif i==3
                line([phase_one
phase_one],ylim,'Color','g');
                line([phase_two
phase_two],ylim,'Color','g');
                line([phase_three
phase_three],ylim,'Color','r');
            elseif i==4
                line([phase_one
phase_one],ylim,'Color','g');
                line([phase_three
phase_three],ylim,'Color','g');
                line([phase_two
phase_two],ylim,'Color','g');
            end
```

```
            title(['participant: ' num2str(j) '  Punch 
Type: ' punchType{i} '  Punch Number: ' 
num2str(n)],'FontSize', 20);
            ylabel('x-axis');
            xlim([-(windowSize/2)+windowOffset 
(windowSize/2)+windowOffset])
            set(gca,'Xtick',[-
(windowSize/2)+windowOffset:50:(windowSize/2)+windowOffset]
)

matlab.graphics.axis.decorator.Baseline('BaseValue',0, 
'Parent',gca, 'Axis',0, 'Visible','on','Color',[0.7 0.7 
0.7],'LineStyle',':');

            bx(2)=subplot(3,1,2);

plot(timeSeries,tempdataFf(:,2),'b','LineWidth',2);hold on;

plot(timeSeries,tempdataBf(:,2),'k','LineWidth',2);

line([data.pID(j).type(i).punch(n).time.duration 
data.pID(j).type(i).punch(n).time.duration],ylim);
            if i==1
                line([phase_two 
phase_two],ylim,'Color','r');
                line([phase_one 
phase_one],ylim,'Color','r');
            elseif i==2
                line([phase_two 
phase_two],ylim,'Color','g');
                line([phase_one 
phase_one],ylim,'Color','g');
            elseif i==3
                line([phase_one 
phase_one],ylim,'Color','g');
                line([phase_two 
phase_two],ylim,'Color','r');
                line([phase_three 
phase_three],ylim,'Color','g');
            elseif i==4
                line([phase_one 
phase_one],ylim,'Color','g');
                line([phase_three 
phase_three],ylim,'Color','r');
                line([phase_two 
phase_two],ylim,'Color','r');
            end

            ylabel('y-axis');
            xlim([-(windowSize/2)+windowOffset 
(windowSize/2)+windowOffset])
```

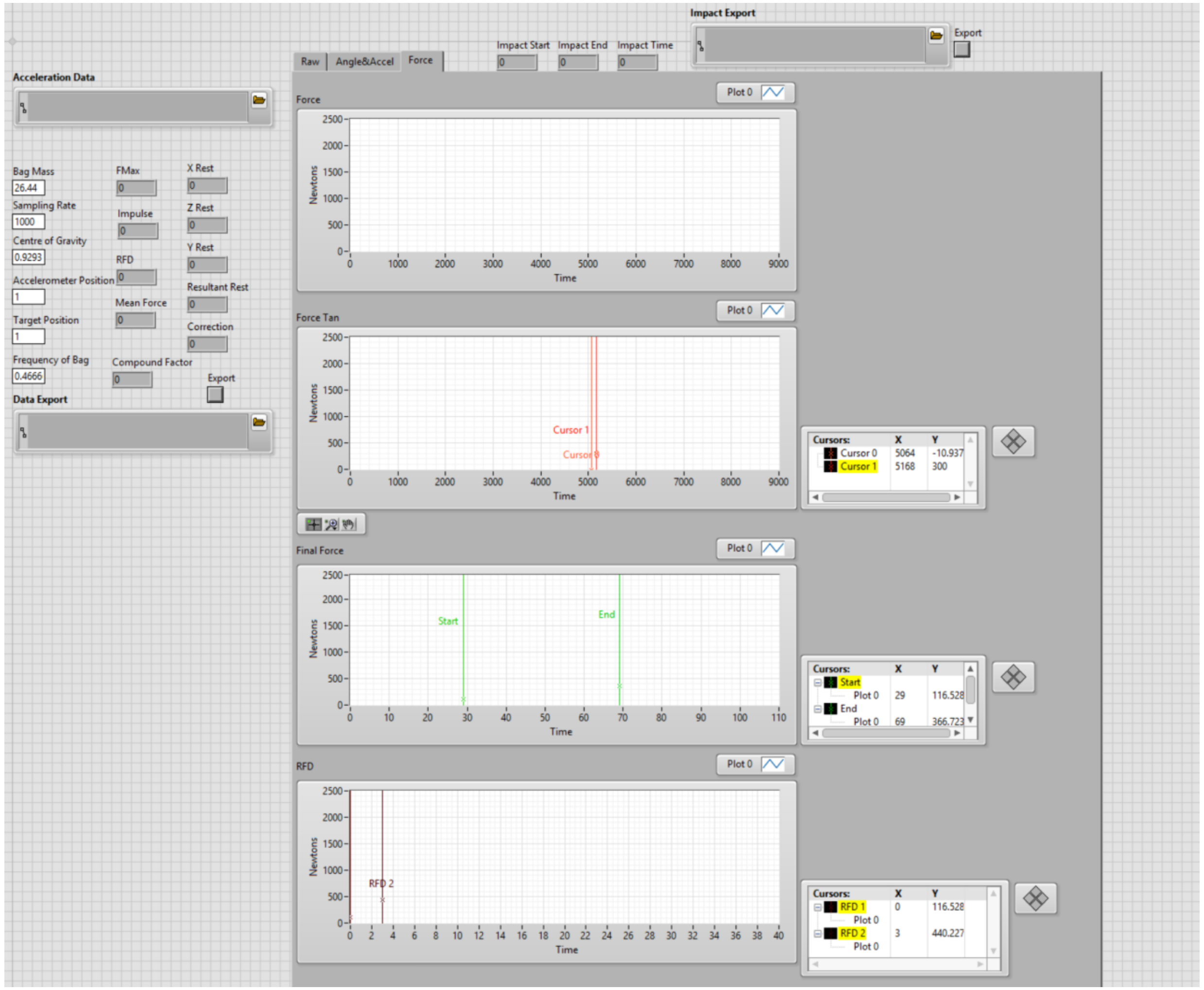
```
            set(gca,'Xtick',[-
(windowSize/2)+windowOffset:50:(windowSize/2)+windowOffset]
)

matlab.graphics.axis.decorator.Baseline('BaseValue',0,
'Parent',gca, 'Axis',0, 'Visible','on','Color',[0.7 0.7
0.7],'LineStyle',':');

            bx(3)=subplot(3,1,3);

plot(timeSeries,tempdataFf(:,3),'b','LineWidth',2);hold on;

plot(timeSeries,tempdataBf(:,3),'k','LineWidth',2);

line([data.pID(j).type(i).punch(n).time.duration
data.pID(j).type(i).punch(n).time.duration],ylim);
            if i==1
                line([phase_two
phase_two],ylim,'Color','g');
                line([phase_one
phase_one],ylim,'Color','g');
            elseif i==2
                line([phase_two
phase_two],ylim,'Color','r');
                line([phase_one
phase_one],ylim,'Color','r');
            elseif i==3
                line([phase_one
phase_one],ylim,'Color','r');
                line([phase_two
phase_two],ylim,'Color','g');
                line([phase_three
phase_three],ylim,'Color','g');
            elseif i==4
                line([phase_one
phase_one],ylim,'Color','r');
                line([phase_three
phase_three],ylim,'Color','g');
                line([phase_two
phase_two],ylim,'Color','g');
            end
            ylabel('z-axis');
            xlim([-(windowSize/2)+windowOffset
(windowSize/2)+windowOffset])
            set(gca,'Xtick',[-
(windowSize/2)+windowOffset:50:(windowSize/2)+windowOffset]
)

matlab.graphics.axis.decorator.Baseline('BaseValue',0,
'Parent',gca, 'Axis',0, 'Visible','on','Color',[0.7 0.7
0.7],'LineStyle',':');
```

```
            c=c+1;
            fig_count=fig_count+1;
            punch_no=punch_no+1;
        end

    end

end
fclose(fID);
```

Appendix 5. Custom built LabVIEW program for the analysis of impact kinetic (raw data analysis)



Appendix 6. Custom built LabVIEW program for the analysis of impact kinetic (impact kinetic data analysis)



Appendix 7. Publication: Measurement of striking impact kinetics via inertial modelling and accelerometery.

This appendix comprises the following conference abstract presented at the *2016 International Society of Biomechanics in Sport* which is in support of Chapter 5.

Reference

Lenetsky, S., Nates, R.J., Brughelli, M., & Schoustra, A. (2016). Measurement of striking impact kinetics via inertial modelling and accelerometery. *ISBS 2016 Conference*. Tsukuba, Japan.

Author contribution

SL: 80%, RJN: 10%, MB: 5%, AS: 5%

Abstract

Striking impact has been explored repeatedly in combat sports. The majority of methods used in the literature require intricate equipment. This study implemented a novel and simple method of measuring impact kinetics using a common, commercially available striking bag. Impulse and peak force of impacts were determined, with reliability and validity statistics obtained from multiple impacts with a custom ballistic pendulum. Test-retest reliability calculations determined that all measures had acceptable reliability (CV≤2.4%). Using linear regression modelling, the coefficient of determination scores displayed a good fit for the model (R2≥0.96) when plotted with a spectrum of pendulum masses. This novel method represents a reliable and valid approach to measuring striking impact kinetics which is easily adaptable to any type of hanging striking target.

Introduction

Striking impact kinetics are central to performance in full contact combat sports (Lenetsky, Harris, & Brughelli, 2013). Varying methods for measuring impact kinetics include the use of force plates or load cells, fluid filled targets, strain gauges and accelerometers inserted internally in striking targets (Smith, Dyson, Hale, & Janaway, 2000). These dynamometers present acceptable reliability and validity data (Busko et al., 2014), however they are typically very expensive and complicated to use. Such issues have limited the use of striking impact dynamometry (SID) to a lab based measure rarely used by practitioners in the field.

The aim of this study was to develop a novel and simple method to measure impact kinetics that can be used effectively and easily by field practitioners.

Methods

The SID developed for this study was comprised of a commercially available striking bag (NZ Boxer™, Teardrop style, Auckland, New Zealand) and an externally mounted wireless triaxial accelerometer (I Measure U Ltd., Auckland, New Zealand), sampling at 1000Hz. A custom built ballistic pendulum was designed to produce a repeatable and controlled SID measurement. This pendulum was designed to be very ridged and consisted of very light cables fitted to a range of commercial dumbbells (Hammer Strength™, Cincinnati, OH, USA). The pendulum was raised to a height of 2.05m for each test impact, loaded with a range of masses to produce a spectrum of impact forces, seen in Figure 1. The masses tested were, 10.8, 12.46, 14.46, 16.4, 18.34, 26.22, 30.4, and 34.5Kgs. A custom-built LabVIEW program (Version 11.0, National Instruments Corp., Austin, TX, USA) was used to analyse the accelerometer data and calculate the force kinetics.

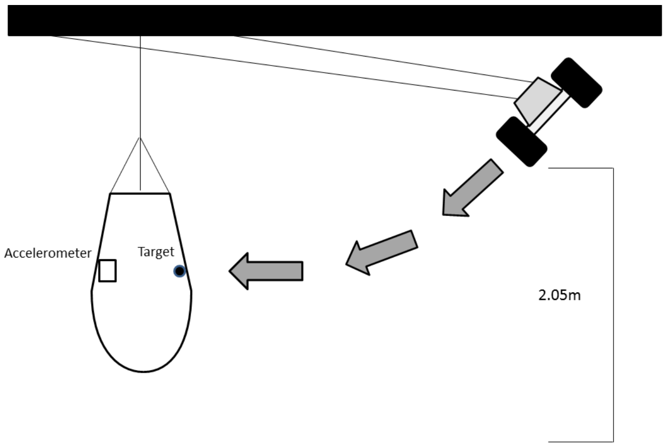


Figure 1. A non-scale diagramme of the experimental set up.

Study design

The ballistic pendulum was impacted against the equipped striking bag. For each pendulum mass, six repeated trials were performed to calculate test-retest reliability results. In addition, the multiple trials were implemented to explore the compliance of the bag to repeated impacts, the result of which may cause compression of the bag and its contents and hence variability in its response. The bag was adjusted to return the contents to their initial state between each mass change. To establish internal validity of the equipped punching bag the varying masses were compared to the findings of the bag calculated through the custom LabVIEW program.

The independent variables were the spectrum of masses used for the impacts. The consistent acceleration of the pendulum, due to the same drop height used for every test, allowed for validity testing as the increase in pendulum mass was predicted to produce linear increases in the dependant variables. Dependant variables were peak force and impulse. Peak force was included due to common inclusion throughout the literature (Pierce, Reinbold, Lyngard, Goldman, & Pastore, 2006; Smith et al., 2000; Walilko, Viano, & Bir, 2005). Likewise, impulse was included as it has primarily been used in the literature to calculate the effective mass of strikes (Lenetsky, Nates, Brughelli, & Harris, 2015). A threshold of 400N was placed on the ending of the force curve for the calculation of impulse due to signal noise caused by the swing of the equipped bag.

Statistical analysis

Mean and standard deviations (SD) were calculated for all dependent variables. All data were log-transformed for reliability statistics. Coefficient of variation (CV%) was calculated to establish the test-retest reliability of the dependent variables. Between trial percent mean change was calculated to explore the influence of repeated impacts. Reliability findings were calculated using a reliability spreadsheet from Sportsci.org (Hopkins, 2012b). Internal validity was examined using an analysis of validity by linear regression spreadsheet (Hopkins, 2012a), analysing the data via linear regression and coefficient of determination.

Results

Impulse ranged between 49-87 N·s and peak force ranged between 2261-3734 N. Between trial percent mean result for the equipped punching bag (Table 1) indicated that there was a levelling off process in the change in mean scores after the first two impacts on the bag in its initial state.

Table 1. Between trial percent mean change

	Trial 2 - 1	Trial 3 - 2	Trial 4 - 3	Trial 5 - 4	Trial 6 - 5
Impulse	2.9	1.4	0.3	-0.2	-0.2
Peak Force	10.4	3.3	0.5	-0.8	0.4

Test-retest reliability (Table 2) displays that removing the first two of the impacts results in similar reliability and was within acceptable ranges (Hopkins, 2000).

Table 2. Test-rest reliability (CV) for the equipped punching bag

	6 Impacts	4 Impacts
Impulse	0.9	1.0
Peak Force	2.5	2.4

Internal validity testing comparing the dependent variables to the mass of the pendulum was found to have a good fit to linear regression models for all variables. Linear regression figures, coefficient of determination, and regression equations can be found in Figure 2. The last four trials were used for this analysis as they were not influenced by the bag compression. There is a slight spread in the findings in Figure 2 due to variations in the angle of impact. This is caused in part by a minor wobble that was inherent in the design of the ballistic pendulum.

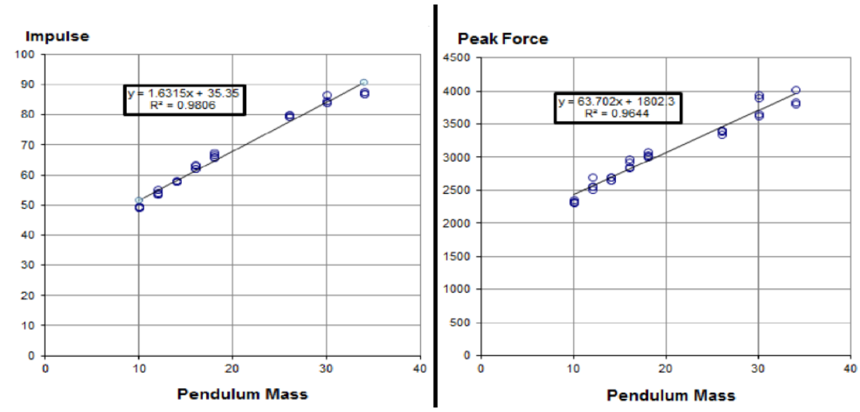


Figure 2. Linear regression of dependent variables and pendulum masses.

Discussion

The purpose of this study was to develop a novel, and simple method of measuring striking impact kinetics that can be used be practitioners in field. The method developed was successful and requires only a commercial striking bag and a triaxial accelerometer. This SID approach produced a reliable measurement of impulse and peak force across multiple impacts. Change in mean scores were found to appropriately illustrate the compressive nature of the equipped bag. On the specific striking bag used in this study it was found that two impacts were needed to compress the bag to a point where the compliant materials in the bag did not affect the readings. Other bags may require a greater or lesser number of impacts to reach a similar point. After an initial observation of this compression point, any striking bag can use this method. Additionally, this method is internally valid in differentiating magnitudes of impulse and peak force across a spectrum of loads.

This internal validity is specific to SIDs as Pedzich et al. (2006) and Busko et al. (2014) argue that due to the variation of the target size and protective padding on the multitude of SIDs used in the literature, accurate comparisons of findings are difficult. In a review of the literature we were unable to find any studies that did not in some way pad the impact target, the striking limb, or both. This makes instinctive sense; a full strength bare knuckle punch, in this example, against an unpadded target would most likely result in injury. Thus, SIDs have been designed in such a way that, while minimizing injury risk, does not accurately measure the true impact kinetics. Some force will always be absorbed by the protective padding during impact, and the time period of the impact varies due to that absorption. This inherent limitation of SID does not mean that measuring impact kinetics in combat sports is meaningless. Rather, in agreement with Busko et al. (2014), we believe that further research must avoid comparison between SIDs as seen previously in the literature (Lenetsky et al., 2013). We suggest that SID need only be: 1) reliable within the device used; and 2) valid in the ability to differentiate kinetic magnitudes to identify differences between and within participants over time. In summary, a SID must produce reproducible results that should only be compared to other results from that same dynamometer, reliability and internal validity. There exists a multitude of devices to measure striking impact kinetics, and while such diversity in the characteristics of the devices exists comparison is problematic. The method presented in this paper offers the most practical approach to SID developed to-date.

Conclusion

This study produced a novel method of striking dynamometry that is reliable and internally valid in measuring impulse, and peak force in striking impacts. The method is relatively simple to use, requiring only a striking bag and a triaxial accelerometer. Additionally, this method does not necessitate any major adjustments to either piece of equipment to provide the information needed to analyse striking performance. This method can also be simply applied to any other hanging striking bag.