FORCE AND VELOCITY JUMP CHARACTERISTICS OF UNIVERSITY-LEVEL FIELD HOCKEY PLAYERS

by

Amori van Jaarsveld

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Supervisor: Prof. Randel Venter

Co-supervisor: Dr Lara Grobler

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The co-authors that form part of the submitted manuscript, Prof Ranel Venter (supervisor) and Dr Lara Grobler (co-supervisor), hereby give permission to the candidate, Amori van Jaarsveld, to include the submitted manuscript as part of her master's thesis. The contribution (advice and support) of the co-authors was kept within reasonable limits, thereby enabling the candidate to submit this thesis for examination purposes. This thesis therefore serves as fulfilment of the requirements for the degree of Masters in Sport Science at Stellenbosch University.

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SUMMARY

Jump testing has been researched for many years. However, no studies have reported on the differences between the concentric phases of the countermovement jump (CMJ) and squat jump (SQJ). The aim of the study, firstly, was to determine the differences in the concentric phase force-, power-, and velocity-time curves of the CMJ and SQJ. Secondly, the study aimed to determine the differences between CMJ and SQJ jump performance variables. Lastly, this study aimed to establish whether rate of force development during the stiffness jump (SJ) could be used as a performance indicator for CMJ and SQJ jump performance.

Twenty-three (n = 23) collegiate field hockey players (n = 10 female (F) and n = 13 male (M); age = 22 ± 1 years (F) and 21 ± 2 years (M)) volunteered to participate in this study. Jump tests were performed on a Bertec Instrumented treadmill (Bertec, USA) at a measurement frequency of 3000 Hz. Data were recorded using Noraxon® MR3.14.52 software (Noraxon, USA). The participant's body mass was measured with a Bertec force plate, to the nearest 0.1 kg. Each participant performed three attempts of the CMJ and SQJ. The best of the three jumps were analysed.

Statistical parametric mapping (SPM) was used to assess the differences between CMJ and SQJ concentric phase force-, velocity-, power-, and displacement-time curves. The analysis was performed using MATLAB R2020a (Version 9.6). The SPM algorithm calculated the statistic field across the whole curve by correcting the critical test statistic threshold using the smoothness of the data, the data size, and the random field behaviour. Data were normalised to 100% of the movement phase analysed. Therefore, results were interpreted in percentage value. SQJ net impulse calculations were adjusted to detect the stillest point prior to the initiations of the concentric phase.

Research questions one and two were answered in **Chapter Four**. Results were reported in the article in **Chapter Four.** A statistically significant difference was observed between 0- and 40% of the force-, power, and velocity-time curves for CMJ and SQJ. Descriptive data analysis showed a significant difference in relative mean and peak force, take-off velocity, mean power between and jump height for the two jumps ($p < 0.05$). However, a non-statistically significant difference was found in relative peak power ($p > 0.05$).

The first null hypothesis (H_0) was rejected, as significant differences were discovered between CMJ and SQJ force-, power-, velocity-time curves during the concentric phase. The second null hypothesis (H_0) was also rejected as a significant difference was found in CMJ and SQJ performance variables. Lastly, the third null hypothesis (H_0) was rejected as moderate and strong correlations between SJ rate of force development and CMJ and SQJ performance outcomes. In conclusion, the eccentric loading has shown to influence the concentric phase of the CMJ as a significant difference was found between 0-40% of the force-time curve. Furthermore, statistically significant differences were found from the initiation up to 75% of the concentric phase of the CMJ and SQJ using SPM analysis. However, no statistically significant difference was observed from 70-100% of the concentric phase suggesting similar performance outcomes for CMJ and SQJ. Descriptive data analysis showed no statistically significant differences in peak power. However, statistically significant differences were found for mean and peak force, mean power, take-off velocity and jump height. Therefore, more attention should be focused on the mechanisms of achieving performance outcomes, rather than focussing on peak performance variables only.

The limitations of the current study were firstly that that no kinematic data was collected. Secondly, the study relied on once-off testing. Lastly, data from men and women were pooled. Future research should include kinematic data for a comprehensive view of an athlete's performance. Furthermore, future research should include testing throughout a periodised training program or an entire competitive season. Future research should further investigate the differences in the concentric phase of CMJ and SQJ between men and women.

Key words: Concentric phase, Countermovement jump, SPM, Squat jump.

OPSOMMING

Daar word reeds jare lank navorsing gedoen oor sprong toetsing. Daar is egter geen studies wat rapporteer oor die verskille tussen die konsentriese fases van die teenbewegingsprong (CMJ) en die hurk sprong (SQJ) nie. Die doel van hierdie studie was eerstens om te bepaal wat die verskille is in die konsentriese fases van krag-, drywing-, en snelheid-tyd kurwes van die CMJ en SQJ. Tweedens het die studie beoog om te bepaal wat die verskil in hoogte is tussen CMJ en SQJ. Laastens het die studie beoog om vas te stel of die styfheid sprong (STJ) tempo van krag ontwikkeling gebruik kan word as prestasie aanwyser vir CMJ en SQJ.

Drie-en-twintig ($n = 23$) universiteit veld hokkie spelers ($n = 10$ vroulik (F) en $n = 13$ manlik (M); ouderdom = 22 ± 1 jaar (F) en 21 ± 2 jaar (M)) het vrywillig aangebied om aan hierdie studie deel te neem. Spring toetse is uitgevoer op 'n Bertec trapmeul (Bertec, USA) teen 'n frekwensie van 3000 Hz. Data is opgeneem met die Noraxon® MR3.14.52 sagteware (Noraxon, USA). Die deelnemer se liggaamsmassa is gemeet met 'n Bertec krag plaat, tot die naaste 0.1 kg. Elke deelnemer het drie pogings aangewend van die CMJ en SQJ. Die beste poging van die drie spronge is geanaliseer via statistiese parameter kartering (SPM).

Statistiese parameter kartering (SPM) is gebruik om die verskille tussen die CMJ en SQJ se konsentriese fase krag-, snelheid-, drywing- en verplasing-tyd kurwes te bepaal. Die analise is uitgevoer deur die MATLAB R2020a (Weergawe 9.6) te gebruik. Die SPM algoritme het die statistiek veld oor die hele kurwe uitgewerk deur die kritiese toetsstatistiek drempel te korrigeer deur gebruik te maak van die egaligheid van die data, die data grootte en die ewekansige -veld gedrag. SPM normaliseer data tot 100% van die beweging wat geanaliseer is. Daarvolgens is resultate as persentasie waardes geïnterpreteer. SQJ se netto impuls berekeninge is aangepas om die stilste punt voor die aanvang van die konsentriese fase op te spoor.

Resultate is in die artikel deurgegee in **Hoofstuk Vier.** 'n Statisties beduidende verskil is waargeneem tussen 0- en 40% van die krag-, drywing- en snelheid-tyd kurwes vir CMJ en SQJ. Beskrywende data analise wys 'n beduidende verskil in die relatiewe gemiddelde- en piek krag, opstygsnelheid, gemiddelde krag tussen en hoogte vir die twee spronge ($p < 0.05$). Daar is egter 'n nie-statisties betekenisvolle verskil gevind in die relatiewe piek krag ($p > 0.05$) nie.

Die eerste nul hipotese (H_0) is verwerp, aangesien beduidende verskille gevind is tussen CMJ en SQJ krag-, drywing -, en snelheid-tyd kurwes van 0-70% van die konsentriese fase. Die tweede nul hipotese (H_0) is ook verwerp aangesien beduidende verskille gevind is in die CMJ en SQJ prestasie veranderlikes. Laastens, die derde nul hipotese (H_0) is verwerp weens gemiddelde en sterk korrelasies tussen die styfheid sprong tempo van krag ontwikkeling in prestasie van CMJ en SQJ. Ten slotte, daar is gevind dat die eksentriese belading 'n invloed het op die konsentriese fase van die CMJ aangesien 'n beduidende verskil gevind is tussen 0-40% van die krag-tyd kurwe. Verder, 'n statisties beduidende verskil is gevind in die aanvang (0-75%) konsentriese fase van die CMJ en SQJ deur die SPM analise te gebruik. Daar is egter 'n nie-statisties beduidende verskil waargeneem van 70-100% van die konsentriese fase wat voorstel dat soortgelyke prestasie uitkomste vir CMJ en SQJ geld. Beskrywende data analise wys nie-statisties beduidende verskille in piek krag. Daar is egter statisties beduidende verskille gevind tussen die gemiddelde en piek krag, gemiddelde drywing, opstygsnelheid en sprong hoogte. Meer aandag moet dus gefokus word op die meganismes van bereiking van prestasie uitkomste, eerder as om te fokus op piek prestasie alleenlik.

Die beperkings van die huidige studie was eerstens dat geen kinematiese data versamel is nie. Tweedens, die studie het staat gemaak op eenmalige toetsing. Laastens, manlike en vroulike data was saamgegooi. Toekomstige navorsing behoort kinematiese data in te sluit vir 'n omvattende oorsig van 'n atleet se prestasie. Verder, toekomstige navorsing moet toetsing versprei oor 'n geperiodiseerde oefenprogram of oor 'n volledige kompetisie seisoen. Toekomstige navorsing moet die verskille in die konsentriese fase van CMJ en SQJ tussen manlike en vroulike atlete ondersoek.

Sleutelwoorde: Teenbewegingsprong, Hurk sprong, Konsentriese fase, SPM.

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LIST OF ABBREVIATIONS AND ACRONYMS

1RM	:	One repetition maximum
%	:	Percentage
α	:	Significance level
BW	:	Body weight
CMJ	:	Countermovement jump
COM	:	Centre of Mass
ConPF	:	Concentric Peak Force
cm	:	Centimetres
CV	:	Coefficient of Variance
DJ	:	Drop jump
EccPF	:	Eccentric Peak Force
et al.	:	et alia (“and others”)
Hz	:	Hertz
ICC	:	Interclass correlation
LPT	:	Linear Position Transducer
MTU	:	Motor-tendon unit
$m.s^{-1}$	:	meters per second
n	:	Sample size
$N.kg^{-1}$	:	Newtons per kilogram
PD	:	Peak displacement
PP	:	Peak power

PV	:	Peak velocity
RFD	:	Rate of force development
RPD	:	Rate of power development
RSI	:	Reactive strength index
SPM	:	Statistical parametric mapping
SSC	:	Stretch shortening cycle
SJ	:	Stiffness jump
SQJ	:	Squat jump
vGRF	:	Vertical ground reaction force
$W.kg^{-1}$	:	Watts per kilogram

OVERVIEW

The thesis is presented in a research article format. One research article (**Chapter four**) was prepared according to the guidelines of the Journal – *Journal of Sport Physiology and Performance* (**Appendix E**). Consequently, the referencing style used in Chapter Four will differ from that of the remaining chapters.

Chapter One: This chapter contains the introduction and problem statement, aims, objectives and the hypotheses of the study. The Harvard Anglia method of referencing was used.

Chapter Two: The purpose of this chapter is to give an overview of existing literature relating to jump testing and field hockey. Again, the Harvard Anglia method of referencing was used.

Chapter Three: This chapter explains study design, sampling (**Appendix A**), ethics (**Appendix B**), research procedures, and statistical analysis. The Harvard Anglia method of referencing was used.

Chapter Four: Research article titled *Concentric phase characteristics during Countermovement and Squat jump performance.* This chapter was written according to the author guidelines of the *Journal of Sport Physiology and Performance* (**Appendix E**). The aim of this article is, firstly, to report on the differences between the concentric phase of the countermovement jump (CMJ) and squat jump (SQJ) force-, power-, and velocity-time curves. Secondly, the article describes the difference in performance variables between CMJ and SQJ. Each participant performed three attempts of the CMJ and SQJ on a Bertec embedded force plate. The best of three jumps were analysed via statistical parameter mapping (SPM) (**Appendix C**). Significant differences were found from initiation up to 70% of the concentric phase. However, a non-significant difference was found from 70-100%. Therefore, suggesting that similar performance outcomes were achieved for force-, power-, and velocity-time curves. Descriptive data analysis showed a non-significant difference found in peak power of CMJ and SQJ (**Appendix D**). Moreover, significant differences were stated for mean and peak force, mean power, take-off velocity and jump height.

Chapter Five: This chapter includes the conclusion of the study, practical applications of the results, limitations of the study, recommendations for research in a similar environment and suggestions for future research.

CHAPTER ONE

INTRODUCTION

A. THEORETICAL BACKGROUND

The power generative capability of athletes enables them to accelerate their bodies, or a segment of their body. Power is also affected by several physiological factors determining an athlete's performance (Haff & Stone, 2015). Torrejón, *et al.*, (2018) found a significant difference in the power production capabilities between novice and experienced athletes due to differences in the physiological adaptations to training. Evaluating the jumping specific force-velocity and power-velocity relationships may identify limitations in an athlete's performance such as imbalances in force and velocity capabilities, lack of intersegmental coordination and poor posture (Giroux, *et al.*, 2015). A method to determine these force-, velocity- and power-time relationships is through jump testing. Jump tests are measurement tools that have become more accessible which, in turn, allows for easier and more frequent identification of limitations in athletes' performance.

The countermovement jump (CMJ) and squat jump (SQJ) have been shown to be two of the most reliable and valid tests to assess lower body power (Markovic, *et al.*, 2004; Rice, *et al.*, 2017). The CMJ is utilised for its capacity to assess an athlete's ability to produce force in a short period of time using the stretch shortening cycle (SSC), while SQJ identifies an athlete's rate of force development during purely concentric movement (Van Hooren & Zolotarjova, 2017). Residual force enhancement, stretch reflexes, and differences in kinematics have no or a small contribution to greater performance during the CMJ compared to the SQJ (Van Hooren & Zolotarjova, 2017).

Another popular jump test is the drop jump (DJ), which is used to assess an athlete's fast-eccentric SSC capacity (Young, Pryor & Wilson, 1995). Stiffness jump (SJ), as a variation of the DJ, is performed in the same manner as the DJ except that an athlete jumps from a self-selected height for seven continuous jumps (Marshall and Moran, 2013; Iacono, *et al.*, 2016). Marshall and Moran (2013), discovered that DJ outperforms CMJ with most performance variables (e.g., rate of force development, power- and force production). The difference in performance between DJ and CMJ is due to DJ producing greater magnitude and rate of eccentric loading, resulting in effective utilisation of the SSC as well as greater force production in the concentric phase. DJ has been shown to be a reliable monitoring tool especially for individual reliability of acute data monitoring and interpretation (Beattie & Flanagan, 2015).

Athletic performance is affected by multiple variables. As mentioned earlier, power is one important aspect of physical performance and is influenced by varied neural and muscular physiological factors (Haff & Stone, 2015). The above-mentioned factors may influence peak power and explosive movements. Athletes are extensively tested in order to find the most reliable assessments to identify performance characteristics. These mentioned jump tests (CMJ, SQJ, DJ and SJ) have extensively been used in research, with many variations in testing protocol, jump instruction and data analysis. However, gaps in knowledge still exist. The current study will be using the novel method of statistical parametric mapping (SPM) for more insightful data analyses. Furthermore, the current study will be comparing the concentric phase of the CMJ and SQJ force-, power-, and velocity-time curves using SPM analysis. To our knowledge, the analysis of the concentric phase of the CMJ and SQJ force-, power-, and velocity-time curves has not been researched. The study will focus on using golden standard testing equipment (force plate).

B. PROBLEM STATEMENT AND RATIONALE FOR THE STUDY

Differences between CMJ and SQJ have been researched for many years. However, SPM analysis has seldomly been used to analyse CMJ and SQJ phase characteristics in sport science. Athletes have been subject to many performance tests through sport science research in an attempt to discern key performance characteristics that may inform better training practices, or potentially mitigate the risk of injury due to fatigue or over-training.

To our knowledge, no research investigated whether a correlation exists between DJ- and CMJ/SQJ performance variables.

C. RESEARCH QUESTIONS, AIMS, OBJECTIVES, HYPOTHESES

Research Question One

Are there differences in selected mechanical features between the concentric phase of the CMJ and SQJ?

Research Aim One

The first aim of the study was to determine the differences in CMJ and SQJ by comparing force-, power-, velocity-time curves using SPM analysis.

Objectives

The objectives for research aim one was to measure, in university-level hockey players, body weight CMJ and SQJ with maximal effort on a force plate to determine:

a) Relative peak velocity, force, and power

Hypotheses

Research hypothesis: Significant differences will be discovered between CMJ and SQJ force-, power-, velocity-time curves when using SPM analysis. CMJ will present statistically significant differences in force-, power-, velocity-time curves due to the eccentric phase affecting the concentric phase.

Null hypothesis (H_0): No statistically significant difference will be identified between CMJ and SQJ for force-, power-, velocity-time curves.

Research Question Two

Are there differences in jump performance- and mechanical variables between the CMJ and SQJ?

Research Aim Two

The second aim of the study was to determine the differences in jump performance- and mechanical variables between CMJ and SQJ for university-level field hockey players.

Objectives

The objectives for research aim two was to measure, body weight, CMJ and SQJ with maximal effort on a force plate in university-level hockey players to determine:

a) Peak velocity, force, and power
b) Mean velocity, force, and power
c) Jump height

Hypotheses

Research hypothesis: A statistically significant difference will be found between CMJ and SQJ jump performance variables. CMJ will present significantly greater force, jump height, take-off velocity and power values due to the eccentric phase.

Null hypothesis (H_0): No statistically significant difference will be observed between CMJ and SQJ jump performance variables.

Research Question three

Is there a relationship between SJ rate of force development and CMJ/SQJ performance outcomes?

Research Aim Three

The third aim of the study was to evaluate the possibility of using RFD during SJ as a performance indicator for CMJ and SQJ.

Objectives

The objectives for research aim three was to measure, body weight, CMJ, SQJ and SJ with maximal effort on a force plate in university-level hockey players to determine:

a) Rate of force development.
b) Jump height.
c) Relative mean force and power.
d) Relative peak force and power.
e) Take-off velocity.

Hypotheses

Research hypothesis: A significant correlation will be established between SJ-RFD and jump performance of CMJ and SQJ. Strong positive correlations will be found between SJ-RFD and CMJ and SQJ performance.

Null hypothesis (H_0): Negative correlations will be found between SJ-RFD and jump performance of CMJ and SQJ.

D. VARIABLES

	Variables
Dependent variables	• Relative mean power ($W. kg^{-1}$) • Relative peak power ($W. kg^{-1}$) • Relative peak force ($N. kg^{-1}$) • Relative mean force ($N. kg^{-1}$) • Mean velocity ($m.s^{-1}$)
Independent variables	• CMJ • SQJ • SJ
Categorical variables	• Age • Level of player (first team squad) • Position • University-level field hockey players

E. ASSUMPTIONS

Certain assumptions regarding the research participants and equipment used were made at the start of the study. It was assumed that participants would complete the consent forms honestly and answer specific questions as completely as possible. It was assumed the participants would execute each test to the best of their ability. It was assumed that participants would attend the required familiarization sessions. It was assumed that the testing equipment elicited valid and reliable data.

CHAPTER TWO

THEORETICAL CONTEXT

A. INTRODUCTION

Jump tests such as CMJ, SQJ, DJ and SJ have extensively been used to determine athletic performance. In a research context many variations in testing protocol, jump instruction and data analysis can be found in published literature.

The present study aimed to investigate force, velocity, and power production relationships within a series of in-place jump tasks to describe jump-specific characteristics in a cohort of team athletes, namely university-level field hockey players. This chapter provides a brief review of relevant and recent literature on the topics mentioned. The literature focuses on how power is produced in the human body, how to determine force and velocity production, jump testing as well as field hockey background and physical demands.

B. FORCE AND VELOCITY PRODUCTION

A large variety of factors that contribute to the physical performance of athletes (Haff & Stone, 2015; Torrejón, *et al.*, 2018). Power, force, and velocity are said to be the primary characteristics determining an athlete's performance.

Power is the rate at which physical work is performed (Equation 1), in other words the product of force and velocity (Haff & Stone, 2015). From a physiological perspective, power is defined as the force of the muscular contraction multiplied by the velocity of the contraction (De Villiers & Venter, 2015). The power generation capability of athletes enables them to accelerate their bodies, or a segment of their body. Therefore, power is regarded as one of the primary physical performance characteristics that distinguishes an excellent athlete from an average athlete (Haff & Stone, 2015).

$$Power\ (\mathrm{W.kg^{-1}}) = \frac{Work(J)}{Time\ (s)}$$

$$= \frac{Force\ (\mathrm{N.kg^{-1}}) \times Displacement(m)}{Time(s)}$$

$$= Force(\mathrm{N.kg^{-1}})\ \times Velocity(m.s^{-1})$$

**Equation 1: Power* (Haff & Stone, 2015)

There are two physiological factors at play in the determination of peak power, namely neural and muscular (Haff & Stone, 2015). These factors influence both the rate and magnitude of muscular contraction which results in explosive/powerful movement. The three main neural factors identified include firing rate, fibre type recruitment and muscular synchronization. Firstly, muscle fibre type is an important physiological factor affecting force and power production (Rice, *et al.*, 2016). To obtain higher power outputs, the recruitment of type II (fast twitch) muscle fibres is essential. Type II muscle fibres have high force development capabilities, has a high recruitment threshold (which may be altered through training) and can relax rapidly thus having a short twitch time. These motor units fatigue easily with low aerobic power and high anaerobic power. There are two types of fast twitch fibres, namely Type IIa and Type IIx fibres (Baechile & Earle, 2016). Type IIa fibres, have greater capacity for aerobic metabolism being surrounded by more capillaries, and have a greater resistance to fatigue than Type IIx (Baechile & Earle, 2016). Recruitment of motor units start with smaller motor units recruited first and larger motor units being recruited last. Secondly, the ability to change motor unit firing rate may lead to an increase in the rate of force development. Lastly, explosive exercise training increases the synchronization of motor unit firing, which increases force production and ultimately increases power production (Haff & Stone, 2015).

The second physiological factor affecting peak power are muscular factors which include the cross-sectional area of the muscle and muscle fibre type (Haff & Stone, 2015). An increase in the cross-sectional area changes the force production capabilities of the muscle. When changes in muscular architecture occur, there is an increase of the number of sarcomeres in series which may increase the contraction velocity. However, increased sarcomeres in parallel increases force production (Haff & Stone, 2015). The second muscular factor is the type of muscle fibre being recruited. Typically type II muscle fibres generate greater shortening velocities, force output and power production in comparison with type I muscle fibres.

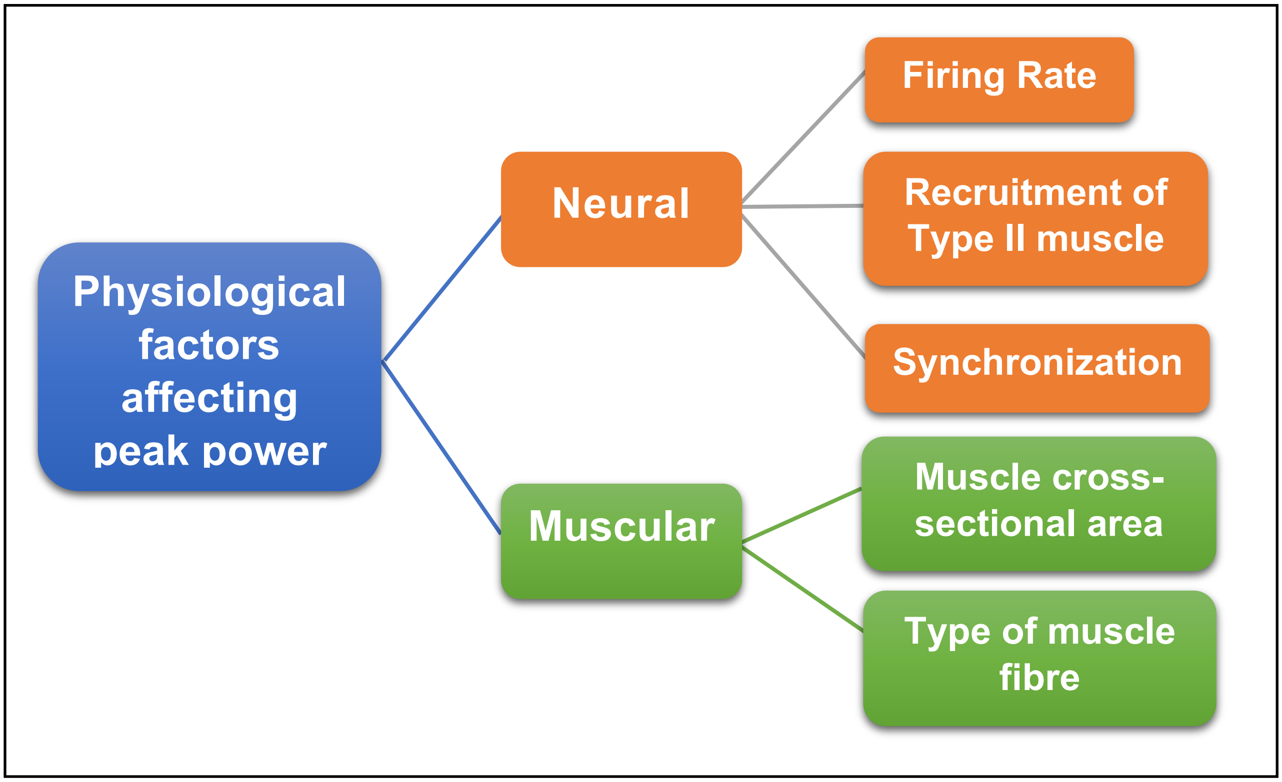

Figure 2.1: Physiological factors affecting peak power output (adapted from Haff & Stone; 2015)

Force and power relationships are essential for athletic performance as increased strength and power will enhance neural drive allowing for increased force production in a shorter period of time (Rice, *et al*., 2016). As seen above, power development is associated with increased motor unit recruitment and firing rates (Rice, *et al*., 2016), which in turn, increases contractile speed.

Training adaptations and physical performance is not only affected by muscular and neural factors but is also affected by gender. Significant differences in strength capabilities have been recorded between men and women (Torrejón, *et al.,* 2018). Moreover, male athletes have been found to have the ability to utilize the stretch shortening cycle (SSC) better than female athletes (Rice, *et al*., 2016). During eccentric muscle contraction, active stretching, and storage of elastic energy in the muscle-tendon unit (MTU) is important. The MTU will shorten due to elastic recoil during concentric muscle action (Rice, *et al*., 2016). The short SSC component occurs within 100–250 milliseconds of muscle activation, therefore influencing rate of force development (RFD) and force production (Ebben, Flanagan & Jensen, 2007; Rice, *et al.*, 2017). Greater eccentric RFD in men has a strong correlation with increased MTU stiffness. Therefore, it can be stated that greater MTU stiffness may lead to greater utilisation of the SSC. A factor that must also be considered is the effect of training on muscle fibre type composition. Exercises including ballistic activities, sprinting and strength training may shift the muscle fibre composition towards type IIa fast twitch muscle fibres (Rice, *et al*., 2016).

There are significant differences in the power production capabilities between novice and experienced athletes due to differences in the physiological adaptations induced by the strength/power training of these athletes (Torrejón, *et al.*, 2018). Furthermore, differences between novice and experienced athletes are also present in the comparison of different sports. Again, the differences in power production capabilities may be due to differences in training and therefore physiological adaptation. It is suggested that the evaluation of force-velocity and power-velocity relationships may identify mechanical, morphological, neuromuscular limitations in an athlete's performance (Giroux, *et al.*, 2015). Therefore, an athlete's power generating capabilities can be gathered from the relationship between the force-velocity and power-velocity curves. An inverse relationship exists between velocity and force (Cronin, McNair & Marshall, 2003; Dugan, *et al.*, 2004; De Villiers & Venter, 2015; Giroux, *et al.*, 2015;). In a resistance training session for instance, the heavier the load that is being lifted, the slower the movement would typically be performed. Thus, the amount of force exerted increases and the movement velocity decreases. When a lighter load is lifted, the movement will take place at a higher velocity.

To evaluate force-velocity and power-velocity relationships, coaches and trainers have been using one repetition maximum (1RM) testing for a variety of exercises like squat, bench press and deadlift. For decades, the 1RM test has been the gold standard for testing power and strength in athletes (Mann, Ivey & Sayers, 2015). As a result, trainers and coaches have been using percentage 1RM (%1RM) to develop training programmes and periodise strength and conditioning components. Numerous studies have since found a near-perfect linear relationship between mean lifting velocity and %1RM (De Villiers & Venter, 2015; Mann, Ivey & Sayers, 2015; Jaric, 2016).

Cormie, McBride and McCaulley, (2009) found that variations in training programmes affected peak performance variables, as well as the shape of the power-, force-, velocity-, and displacement-time curves of the CMJ.

C. DETERMINING FORCE AND VELOCITY PRODUCTION

Jump tests are regarded as an easy and manageable way to measure force and velocity production during a ballistic movement both in the gymnasium and on the field. Measurement tools have become more accessible and jump tests can easily be used to identify mechanical, morphological, and neuromuscular limitations in an athlete's performance (Giroux, *et al.*, 2015). For the current study, SQJ, CMJ and SJ were chosen. All the above-mentioned jump tests can be used to assess lower body power (Markovic, *et al.*, 2004).

1. COUNTERMOVEMENT JUMP AND SQUAT JUMP

When performing the CMJ, athletes are instructed to drop their centre of mass by flexing their knees, hips, and ankles, before jumping vertically off the ground. The CMJ makes use of the SSC, storing elastic energy within the MTU (Bobbert, *et al*., 1996). During the SQJ the athlete initiates the jump from a semi-seated position. No downward or countermovement is allowed during SQJ. Previous research has reported a greater jump height during the CMJ compared to SQJ (Bobbert, *et al*., 1996; Walsh, *et al*., 2007a). Bobbert, *et al.*, (1996) provided four hypotheses as to why CMJ exhibits a greater jump height than SQJ. Firstly, athletes might not be familiar with the SQJ movement. Secondly, during the SQJ, voluntary muscle contraction cannot generate high levels of force before initiating the concentric contraction. Thirdly, the difference between the two jumps may relate to the storage of elastic energy and the utilization of that energy. Lastly, potentiation during CMJ increases the speed of pre-stretch and decreases time before concentric contraction thus enhancing force production. Furthermore, Walsh, *et al.,* (2007) determined that arm swing contributes more to jump height than a countermovement. In the study by Walsh, *et al*., (2007) 25 female and 25 male collegiate athletes performed four jumps with maximal effort, namely: SQJ, CMJ without arm swing, SQJ with arm swing (SQJA), and counter movement with arm swing (CMJA). Each of the jumps was performed five times with one to three minutes rest between jumps. Results indicated that for both sexes, CMJA had the highest peak power and jump height. Peak power values for men were 4057 ± 613 W, 4020 ± 644 W, 4644 ± 656 W, and 4747 ± 669 W, respectively, for the four jumps. The female power values were 2543 ± 501 W, 2445 ± 486 W, 2842 ± 579 W, and 2788 ± 570 W, respectively, for the four jumps. Jump heights for men were 29.6 cm, 31.0 cm, 36.0 cm, and 38.0 cm, respectively, and those of women were 21.0 cm, 22.0 cm, 26.0 cm, and 27.0 cm, respectively. Arm swing thus made a difference in jump height, more so for men than women, which might be attributed to the greater upper body strength found in men (Walsh, *et al*., 2007).

Although factors such as arm swing, familiarity with the CMJ and SJ and voluntary muscle contraction have an influence on the jump heights achieved in the CMJ and SJ, Bobbert, *et al*., (1996) attributed the greater jump height of CMJ to the countermovement allowing for greater joint moments at the start of the push-off. With the CMJ, more mechanical work can be produced after the countermovement compared to the SJ. Linthorne, (2021) has recently argued against the notion of mechanical power as determinant of jump height when he stated that power calculations might produce artificially strong correlations between jump height and power. The author stated that power, as a compound variable, is calculated from the product of instantaneous ground reaction force and instantaneous velocity, therefore, a correlation between jump height and power is artificially inflated by the near-perfect correlation between jump height and the velocity at peak power (Linthorne, 2021). An increase in mechanical power in a jump would not necessarily represent an improvement in neuromuscular capacity or stretch-shorten cycle function. To interpret a change in mechanical power, it is advised that other variables such as countermovement depth, rate of countermovement, as well as the timing of joint extensions should be investigated.

McMahon, Rej and Comfort, (2017) performed a jump test analysis of 14 men and 14 women to determine the difference in phase characteristics. Men achieved greater jump height by displacing their COM more than their female counterparts. This increased COM displacement was accompanied by greater take-off velocity and concentric net impulse. Increased relative power (i.e., W/kg) was observed during the concentric phase of the CMJ and was due to an increase in velocity just before the take-off phase of the jump (McMahon, Rej & Comfort, 2017). Relative peak force during the eccentric and concentric phases did not show a significant difference between men and women.

When analysing CMJ data, strength and conditioning coaches and trainers gain valuable information about their athletes. Changes in the force-time curve are due to specific training adaptations (Cormie, McBride & McCaulley, 2009; Laffaye, Wagner & Tombleson, 2014). Neuromuscular adaptations should increase force production during eccentric movement through increased interaction of contractile and elastic elements as well as utilisation of the SSC (Laffaye, Wagner & Tombleson, 2014). Rate of force development (RFD) plays a significant role in explosive movements and gives valuable information about an athlete's ability to utilise their SSC. Rate of force development can be defined as the rate at which contractile force rises at the beginning of muscle action (Ebben, Flanagan & Jensen, 2007). It was suggested that eccentric rate of force development is a stronger predictor of jump height as it reflects an athlete's ability to utilise the SSC (Laffaye, Wagner & Tombleson, 2014).

Researchers have reported on jump tests of both men and women from a variety of sporting backgrounds. Laffaye, Wagner and Tombleson, (2014) investigated whether "sport specific signatures" existed when interpreting force-time variables in athletes from various sports. It was reported that athletes from outdoor team sports increased jump height performance compared to indoor team sports (59.1 ± 8.6 cm for baseball players to 46.8 ± 12.7 cm for basketball players ($p = 0.0001$)). The researchers also revealed that sporting background influences jump profiles. Athletes from indoor sports (basketball and volleyball) showed lower force capabilities compared to their outdoor-sports counterparts, with volleyball having greater time capabilities. In contrast, outdoor team sports (football and baseball) had greater force capabilities, creating an explosive profile (Laffaye, Wagner & Tombleson, 2014). Analysis of the CMJ is crucial to revealing specific weaknesses in athletes such as lack of adaptation, coordination, and posture. Giroux, *et al.,* (2015) examined the effect of sport background on the force-velocity and power-velocity profiles of elite athletes in loaded SQJs. The study included participants ($n = 95$) from cycling (track and BMX), fencing, taekwondo, and athletic sprinting, as well as 15 control (active) subjects. Procedures included a familiarisation session and a test session. Jump height was obtained using an OptoJump

Next optical measurement system (Microgate, Bolzano-Bozen, Italy). The movement instructions were not specified in the article. Force-velocity profiles were found to differ between an optimal profile and elite athletes due to enhanced muscular capacities (Giroux, *et al.*, 2015). Furthermore, findings from this study suggest that power-velocity and force-velocity relations of a SQJ test are specific to an athlete's sporting background (Giroux, *et al.*, 2015). To our knowledge limited research has been done to investigate force-velocity and power-velocity relationships in field hockey players.

Even though men can achieve a greater jump height than women, Ebben, Flanagan and Jensen, (2007), found that athletes with similar training backgrounds and experience reduce gender differences in jumping variables. As previously discussed, research has shown physiological differences between men and women (Haizlip, Harrison & Leinwand, 2015). However, no difference in RFD was recorded during this study (Ebben, Flanagan & Jensen, 2007). Time to take-off data showed no statistically significant difference between men and women. Therefore, suggesting that women develop force at the same rate as men. These conflicting findings between studies could be due to the inclusion of athletes of different abilities, differences in training backgrounds between athletes, as well differences in training experience of participants. Future research is required to investigate power-velocity and force-velocity relations, jump height and RDF in field hockey players as this is presently unknown.

As mentioned above the CMJ and SQJ have different movement patterns. The CMJ relies on the ability to rapidly produce force using the SSC (van Hooren & Zolotarjova, 2017), whereas, the SQJ performance relies on rapid force development from the concentric movement only (Van Hooren & Zolotarjova, 2017). The phases of the CMJ are defined by Rice, *et al.*, (2016) include: the initiation, unweighted phase, eccentric phase, coupling phase and the concentric phase. The initiation of the unweighted phase shows a negative force development as well as negative acceleration (Rice, *et al*., 2016). The peak negative force value will be seen during the eccentric phase (Rice, *et al*., 2016). The period during which the force turns from negative to positive is called the coupling phase or eccentric-concentric phase. During this phase, rate of force development (RFD) is calculated. Peak force is reached during the concentric phase whereafter an athlete will take-off. McMahon, Rej and Comfort, (2017), specifically pin-pointed the phases of the CMJ as the eccentric phase occurred between peak negative and zero COM (centre of mass) velocity. The concentric phase occurred the instant COM velocity exceeds 0.01 $m.s^{-1}$ (McMahon, Rej & Comfort, 2017). Take-off occurred when vertical force was less than 5 times that of the SD of body weight (McMahon, Rej & Comfort, 2017). More recently Sole, *et al.*, (2018) identified six phases of the CMJ, the unweighted phase, stretching phase, net impulse phase, propulsion-acceleration I phase, propulsion-acceleration II phase, and propulsion-deceleration phase. Currently, different definitions are used to describe the same phase of the CMJ, which may lead to confusion when interpreting or comparing results from different studies.

It is also important to consider the impact of jump ability on the phase characteristics of the CMJ. When comparing athletes in high performance, middle performance, and low performance groups, it was found that there were significant differences in relative phase magnitude and impulse between groups (Sole, *et al*., 2017). However, no significant differences were found between phase durations. However, the study by Sole, *et al*. (2017) included athletes from different sporting backgrounds and only the Force-time data was analysed without considering other variables. Different sports have different physical demands and it can therefore be argued that training background may affect jump performance, for example, comparing jumping sports and non-jumping sports. Cormie, *et al*., (2009) completed a cross-sectional and longitudinal investigating the impact of power training on power-, force- and velocity curves of the CMJ. A force plate (BP6001200, AMTI, Watertown, Mass) as well as two linear position transducers (LPTs) (PT5A-150, Celesco Transducer Products, Chatsworth, Calif) were used. The researchers calculated peak power (PP), peak concentric- (ConPF) and eccentric-force (EccPF), peak velocity (PV), rate of force development (RFD) and peak displacement (PD). The participants were given specific movement instructions, thereafter data were normalized and resampled to represent relative time to complete the movement (0-100%). Therefore, allowing all power, force, velocity, and displacement curves to be expressed over equal periods of time. It was discovered that jumpers displayed significantly greater PP, ConPF, EccPF, PV, PD, RPD, acceleration, force at PP, and velocity at PP than non-jumpers. Analysis of the power, force, and velocity curves revealed significant differences between the jumpers (athletes, n = 12) and non-jumpers (untrained individuals, n = 18) throughout the movement. The 12-week longitudinal examination of 18 untrained men (10 training group and 8 control group) showed no differences existed in any of the performance variables at baseline (see Figure 2.2) (Cormie, *et al*., 2009). After training, PP, EccPF, PV, PD, concentric RFD, eccentric RFD, and velocity at PP improved significantly. The power training intervention thus led to a significant increase in performance variables and overall power production over a 12-week period. However, the authors highlighted that no significant changes occurred in the gradient of the power-, velocity-, displacement-time curves. Thus, emphasizing the lack of training adaptation in rate of power development or in acceleration capabilities. Therefore, the analysis of the power-, force-, velocity and displacement-time curves can give insight into the nature of adaptation due to a training program.

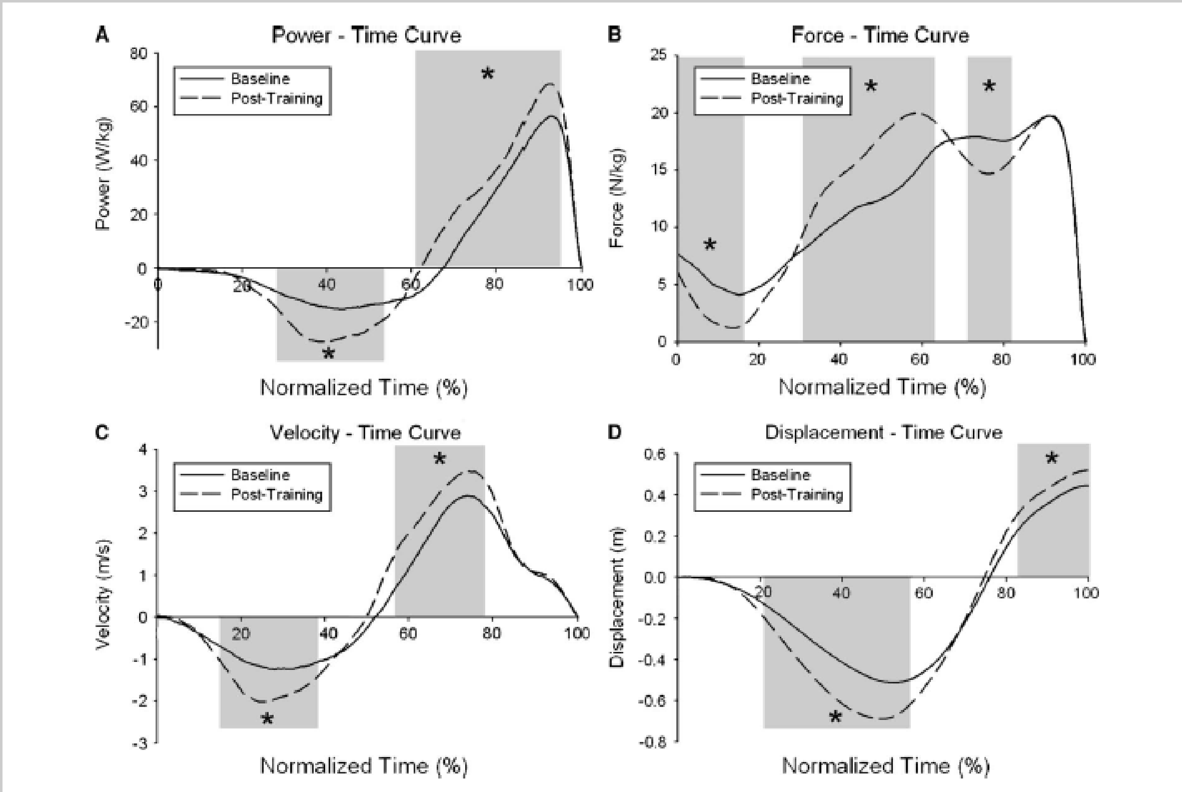

Figure 4. Comparison of the average (390–506 Hz; *n* = 10) power-time (A), force-time (B), velocity-time (C), and displacement-time (D) curves during a countermovement jump (CMJ) before and after 12 weeks of power training. *Significant difference ($p \leq 0.05$) between baseline and posttraining in A) power from 29.2 to 54.6% and 60.4 to 97.4%; B) force from 0.0 to 16.6%, 32.2 to 62.0%, and 70.8 to 81.4%; C) velocity from 15.2 to 39.6% and 57.2 to 78.8%; and D) displacement from 20.4 to 57.8% and 83.4 to 100%.

Figure 2.2: Comparison of the average power-time (A), force-time (B), velocity-time (C) and displacement-time (D) curves during a countermovement jump before and after 12 weeks of power training (With permission, Appendix G).

Hoffman, *et al*., (2005) set out to explore the effect of eccentric loaded and unloaded SQJ training in football players during the strength/power phase of a five-week periodised off-season resistance training program. The best out of three jump attempts were recorded. The athletes were divided into three groups. The first group performed a jump squat exercise using both concentric and eccentric phases of contraction (CE; n = 15). A second group performed the jump squat exercise using the concentric phase only (n = 16), and a third group served as control (CT; n = 16). There were no significant differences between the groups for power, vertical jump height, 40-yard sprint and agility performance. However, there were significant differences between the CE and CT groups in 1RM squat (65.8 kg and 27.5 kg, respectively) and 1RM power clean (25.9 kg and 3.8 kg, respectively). During the off-season all the groups performed traditional power and Olympic lifting exercises as well as sprint and agility training. It may be debated that these exercises provided sufficient training stimulus that led to similar performance improvements between the groups (Hoffman, *et al*., 2015). The results of the study indicate that the inclusion of jump squat training into off-season training (relative short duration of five weeks) may enhance the training stimuli which in turn may improve strength, only when the eccentric phase is loaded (Hoffman, *et al*., 2015).

Turner, *et al.,* (2012), examined the influence of load on peak power output (PPO), peak barbell velocity, and peak vertical ground reaction force (vGRF) during the SQJ in a group of professional rugby players (n = 11). The FT 700 Power System (Fittech, Australia) was used for data collection. No specific movement instructions were stipulated in the study, although weighted barbells were used. Rugby players participated in a familiarisation session (with full testing protocol) and a supervised warm-up was conducted prior to testing. In resistance trained professional rugby players the optimal load for eliciting PPO during the loaded SQJ occurs at 20% 1RM. Decreases in PPO and velocity were observed, as well as increases in vGRF when load was increased. PPO and peak vGRF were thus affected by load (Turner, *et al*., 2012).

Although the CMJ and SQJ have been used extensively to test athletes, several shortcomings have been identified (Salaj & Markovic, 2011). Markovic, *et al.* (2004) stated that due to limited testing on large samples, the reliability and factorial validity of these exercises for large sample sizes are inadequate. Addressing this limitation, Makovic, *et al*., (2004) included 93 male physical education students in the study, using the Ergojump measuring system. They verified these jumps to be the most reliable and valid tests for measuring explosive lower body power in their sample. Even though CMJ and SQJ were confirmed as the most reliable and valid tests to assess lower body power (Markovic, *et al*., 2004; Rice, *et al*., 2017), unstandardized methods of data collection and analysis can lead to vastly different maximum power results (Dugan, *et al*., 2004; Salaj & Markovic, 2011). The following topics, as reviewed by Dugan *et al*., (2004), contributed to different results, namely, data collection equipment, inclusion, or exclusion of body weight in the calculation of power, free weight versus Smith machine SQJ, reporting of average versus peak power, reporting of load intensity, and instructions given to participants (Dugan, *et al*., 2004).

The common method of waveform analysis is discrete point analysis (DPA). DPA examines pre-selected data points in order to reduce excess data (Warmenhoven, *et al*., 2018). Although extensively used, DPA requires prior knowledge of the movement tested in order to select specific data points to be analysed. Therefore, relevant information may be discarded (Warmenhoven, *et al*., 2018). In order to overcome these limitations, statistical methods have been designed to allow the analysis of the entire time-series data. One of the statistical methods of data analysis is statistical parametric mapping (SPM). SPM has been used in a variety of sports and movements such as soccer kicking, running, underwater sculling, CMJ and landing techniques (Warmenhoven, *et al.*, 2018; Colyer, Graham-Smith & Salo, 2019; Kipp, Comfort & Suchomel, 2019). SPM allows researchers to analyse each time-series variable as a single data point and is believed to be a better method of analysing time-series data compared to DPA curve analysis due to the fact that analysis of the whole waveform can be performed from time-series data (Warmenhoven, *et al.*, 2018; Kipp, Comfort & Suchomel, 2019).

The information given in Table 2.1 summarises the articles used in the current thesis. These articles were selected to investigate 1) force, power and velocity relationships 2) training background effect on the above-mentioned relationships 3) comparisons of the influence of using arm swing vs no arm swing 4) jumper vs non-jumper

Table 2.1: Summary of articles between 1996 and 2017 reporting on Countermovement jump and Squat jump

Authors	Sample size	Type of sport	Type of athletes	Equipment used	Jump test	Variables Tested	Outcome
Bobbert, *et al.,* 1996	n = 6	Volleyball	All male	Electronically shuttered cameras, force plate and EMG	CMJ & SQJ	JH	The method of testing is a reliable, inexpensive, and easy alternative to assess CMJ performance and individualized F–v profile. CMJ achieved a higher jump height than SQJ
Cormie, *et al.,* 2009	n = 30	Football, track, field athletes and active men.	n = 12 Athletes n = 18 active men	Force plate and two linear position transducers	CMJ	PP Concentric PF Eccentric PF PV Peak displacement Concentric RFD Eccentric RFD Concentric RPD Acceleration Force at PP Velocity at PP Time to take-off	Significant differences between jumpers and non-jumpers. The longitudinal examination revealed greater force output development in the eccentric phase of CMJ.
Ebben, *et al.,* 2007	n = 45	Division 1 field and track athletes	n = 24 (M) n = 21 (F)	Force plate (1000Hz)	CMJ	Time to take-off RFD	The TTT ($p = 0.08$) or RFD ($p = 0.11$) showed no statistically significant differences between men and women. RFD showed no correlation to CMJ ($r = 0.19$, $p= 0.22$), though to TTT ($r = - 0.33$, $p = 0.03$). Results indicate that women have similar RFD to men.
Giroux, *et al.,* 2015	n = 95 n = 15	Elite Cycling, Fencing, Taekwondo, Athletics	Athletes- n = 38 (F) n = 57 (M) Control-n = 7 (F) n = 8 (M)	OptoJump (optical measurement system)	SQJ	Theoretical maximal force F0, maximal velocity v0, maximal power P theoretical maximal optimal velocity v0th force F0th	Sprinters and cyclists generate greater force than other groups. Force was significantly lower than optimal profile. Velocity was significantly higher than the optimal velocity profile for fencers, control participants, male sprinters, and taekwondo practitioners. Force-velocity profiles may appear different due to chronic practice of a specific exercise.

Hoffman, *et al.,* 2005	n = 47	College Football	n = 47 (M)	Position transducer and vertec.	CMJ, SQJ and 1 RM Squat	JH	No significant differences were seen in power, vertical jump height, 40-yd sprint speed and agility performance between groups. Furthermore, no significant differences were found in integrated EMG activity between groups. Significant differences in 1RM squat (65.8 and 27.5 kg, respectively) and 1RM power clean (25.9 and 3.8 kg, respectively) were reported between the CE and CT groups. Results indicate the benefits of the jump squat training program (5-week duration).
Laffaye, *et al.,* 2014	n = 273	Elite collegiate football, basketball, baseball, and volleyball	n = 189 (M) n = 84 (F)	Force plate (500Hz)	CMJ	Eccentric RFD, total time, eccentric time, Ratio between eccentric and total time average force, impulse momentum.	Results reported a correlation between jump height and CON-F (r = 0.57) and ECC- RFD (r = 0.52). Force variables were significantly different between men and women ($p < 0.01$), whereas no significant difference was reported time variables. Principal component analysis (PCA) showed a 76.8 % variance in JH. Furthermore, PCA revealed that temporal and force can predict jump height.
Markovic, *et al.,* 2004	n = 93	Physical Education Students	n = 93 (M)	Ergojump	CMJ & SQJ	JH JL	CMJ and SQJ are the most reliable and valid tests for the estimation of explosive power of the lower limbs.
McMahon, *et al.,* 2017	n = 28	Regional Netball players and Professional Rugby players	n = 14 (M) n = 14 (F)	Force plate (1000Hz)	CMJ	JH Movement Time RSImod Leg Stiffness Eccentric COM Displacement Concentric COM Displacement Peak Eccentric Force Peak Concentric Force Peak Eccentric Power Peak Concentric Power Peak Eccentric Velocity Peak Concentric Velocity Eccentric Impulse Concentric Impulse	JH, RSImod, relative peak concentric power, and eccentric and concentric displacement, velocity, and relative impulse were all greater for men (g = 0.58–1.79) compared to women. Relative power-, velocity-, and displacement-time curves were greater for men than that of women. The CMJ performance may distinguish between sexes, due to men being able to express larger concentric impulse resulting in greater jump height.

Sole, *et al.,* 2017	n = 30	Division 1 collegiate athletes (10 different sports)	n = 15 (M) n = 15 (F)	Force plate (1000Hz)	CMJ	Phases of the CMJ F-t curve were determined and then characterized by their duration, magnitude, area (impulse), and shape (shape factor).	Statistically significant phase-by-performance group interactions were observed for relative phase magnitude ($p < 0.001$), relative phase impulse ($p < 0.001$), and shape factor ($p = 0.002$). Relative phase magnitude ($p < 0.001$) and relative phase impulse ($p < 0.001$) reported a statistically significant difference during phases between men and women. Athletes with greater jump performance showed larger relative magnitude and impulse. Finally, jump height was related to the initial rise in force.
Rice, *et al.,* 2017	n = 16	Division 1 Basketball	n = 8 (M) n = 8 (F)	Force plate (1000Hz)	CMJ	RFD, RPD, JH (All power-, and force-time variables)	Jump height was significantly different ($p \leq .05$) between males and females. Absolute force was greater in males during the concentric phase, however relative force showed no significantly different ($p \geq .05$). Significance was found in absolute concentric impulse between males and females, moreover no significant difference was reported for relative RFD, RPD, PF. Significantly greater impulse was reported for males during the eccentric phase and PP (relative and absolute) during the concentric phase of the CMJ. However, when comparing strength matched individuals, eccentric phase impulse and concentric phase PP are influenced by gender.
Turner, *et al.,* 2012	n = 11	Professional Rugby	n = 11 (M)	Force plate and Linear position transducer	SQJ	PP, PF, PV, vGRF	The optimal load for eliciting PPO during the loaded SQJ in the range measured occurs at 20 % 1RM JS, with decreases in PPO and BV, and increases in vGRF, as the load is increased, although greater PPO likely occurs without any additional load.
Walsh, *et al.,* 2007	n = 50	College students	n = 25(M) n = 25(F)	Force plate	CMJ & SQJ	Positive and negative P, V, displacements, vGRF	Greater jump height was reported for CMJ compared to SQJ. Furthermore, arm swing increased jump height for both genders. Jump height was significantly increased with the use of arms wing for men compared to women.

*Countermovement jump (CMJ), Squat Jump (SQJ)

**Rate of force development (RFD), rate of power development (RPD), jump height (JH), jump length (JL), peak power (PP), peak force (PF), peak velocity (PV), vertical ground reaction force (vGRF)

From the 12 studies summarised in Table 2.1 it is evident that there is still a need to conduct more research on the use of CMJ- and SQJ assessments in sport in general. The results of previous research seem to be inconsistent and often contradictory. This is possibly due to the lack of standardized testing protocols. These 12 studies showed variation in sporting background (volleyball, basketball, baseball, netball, rugby, track, and field athletes etc.). Table 2.1 also indicates that a variety of equipment was used for jump testing equipment. Eight studies used force plates, two used linear position transducers, one study used Egrojump and the other used Optojump. Power calculations are also up for debate as some studies include body weight when calculating power, and other studies excluded body weight. In closing, Table 2.1 shows a large variation in sample sizes that were tested, ranging from as little as six participants to 273 participants per study. The current study should contribute to the current knowledge by focussing on the use of gold standard equipment in the assessment of CMJ and SQJ variables using SPM analysis in university level field hockey athletes.

2. DROP JUMP AND STIFFNESS JUMP

Drop jump (DJ) tests are used to assess an athlete's fast-eccentric SSC capacity (Young, Pryor & Wilson, 1995). Research has shown that DJs can be prescribed as a plyometric exercise to improve CMJ height (Marshall & Moran, 2013; Iacono *et al.*, 2016). Even though these studies tested different performance variables (as seen in Table 2.2), they both reached the same conclusion, in that significant differences could be found in the force-time components of DJ and CMJ. When interpreting the movement of DJ, the jump requires an athlete to have as little ground contact time as possible. Therefore, increasing the eccentric RFD, shorter concentric phase, which in turn will lead to an increase in peak power and peak force. These differences are indicative of the increased utilisation of the SSC in the DJ (Marshall & Moran, 2013). Iacono, *et al.*, (2016), stated that take-off velocity determines the success of a vertical jump. Their results indicated that after vertical DJ training, a greater ground reaction force was recorded with a shorter contact time for CMJ. Moreover, they discovered development of CMJ performance measures such as increased relative impulse, increased reactive strength index (RSI) and leg stiffness (Iacono, *et al.*, 2016), thereby indicating increased utilisation of the SCC after DJ training.

DJ performance can be altered through verbal instructions (Young, Pryor & Wilson, 1995; Arampatzis, *et al.*, 2001). When instructed to jump to maximum height, participants achieved greater jump height compared to any other instructions trying to maximise jump height. However, when participants were instructed to jump with minimal ground contact time a decreased jump height was achieved (Young, Pryor & Wilson, 1995). It can be argued that the second instruction allows participants to make use of their fast-eccentric SSC (Young, Pryor & Wilson, 1995). It is therefore important to standardise the instructions provided to athletes during testing as this may have a significant impact on the performance outcome. The researchers also found that changes in leg stiffness can occur due to changes in contact time. Arampatzis, *et al.*, (2001) proposes that optimal leg stiffness exists. Therefore, the mechanical power output and the amount of muscle activation during the pre-activation phase of a DJ can be maximized by optimal leg stiffness which can be altered through verbal instruction as mentioned above.

Beattie and Flanagan (2015) established inter-trial and inter-day reliability for DJ test from a 40 cm height. Inter-trial reliability indicated a coefficient of variance (CV) of 5 % and intraclass correlation (ICC) of 0.90. Inter-day reliability indicated a CV of 8 % and ICC of 0.93. It was thus indicated that DJ as a monitoring tool is reliable. However, the smallest worthwhile change is smaller than the coefficient of variation (CV), therefore, each athlete's CV should be used as their own control in individual monitoring. Previous literature demonstrated good reliability of DJ reactive strength index, Beattie and Flanagan (2015) Published reliability data are averaged group data which may be highly specific to the population and the context it is gathered in (Beattie & Flanagan, 2015). As a result, certain individuals within a group may exhibit reliability levels above or below aggregated reported means.

The information in Table 2.2, summarises articles assessing drop jump performance as trivial amounts of research cover the topic of stiffness jumps. Due to time constraints stiffness jumps and derivatives of DJ was not added to the summarised table.

Table 2.2: Summary of articles between 1995 and 2016 reporting on Drop Jumps

Authors	Sample size	Type of sport	Type of athletes	Equipment used	Jump test	Variables Tested	Outcome
Arampatzis, et al., 2001	n = 15	Not specified	Not specified	Force plate (1000Hz)	DJ	Take-off V Mechanical P	Verbal instruction can influence leg stiffness and contact time. Different leg stiffness may lead to max take-off velocity being achieved. There is an optimum stiffness value to maximize mechanical power.
Beattie & Flanagan, 2015	n =15 n =9	Rugby	Elite Junior international Male	Electronic contact mat (Ergojump)	DJ	CT, JH, DJ-RSI	Monitoring tool is reliable but the SWC < CV. Practitioners should calculate individual athlete's own reliability data to optimise the interpretation of data.
Iacono *et al*., 2016	n = 18	Elite Handball	n = 18 (M)	Force plate (500Hz)	VDJ, HDJ and CMJ	vGRF, Relative impulse, Leg spring stiffness, CT, RSI	The HDJ improved of the sprint time and COD performance, whereas the VDJ improved in the vertical jump. Moreover, the VDJ training increased peak ground reaction forces, relative impulse, leg spring stiffness, CT, and RSI. HDJ training increasing the step length and reducing the CT on COD. Therefore, different plyometric exercises play crucial role in optimizing performances.
Marshal & Moran, 2013	n = 105	Football, Soccer, Basketball	n = 105 (M)	Force plate (250Hz)	CMJ and DJ	JH	The countermovement DJ training group increased their CMJ height by 2.9 cm (6 %) (P < 0.05) in comparison to bounce DJ (-0.2 cm, -0.4 %) and the control group (-0.1 cm, 0.2 %).
Young, et al., 1995	n =17	Not specified	Physically Active, Sport involving jumping and volunteers (M).	Kistler Force Plate and video tape	DJ and CMJ	JH, CT	When jump height is the only objective CMJ and DJ characteristics were the same. A decrease of CT will affect jump height. Thus, different instructions affect jump performance.

* Countermovement jump (CMJ), Drop jump (DJ), Vertical drop jump (VDJ), Horizontal drop jump (HDJ)

**Jump height (JH), ground contact time (CT), reactive strength index (RSI), vertical ground reaction force (vGRF)

From Table 2.2 it is evident that there is limited published research on the DJ as a performance jump test. DJ research mainly used male participants, and to our knowledge no research has been conducted on SJ and its correlations with CMJ and SQJ. A variation in testing protocols, standard of equipment used, and different performance variables reported has led to disparity in literature. The current study will focus on using golden standard equipment, while researching correlations between SJ, RFD and CMJ as well as SQJ performance variables.

The DJ has specific technical demands which makes it difficult to teach in a short period of time. To lower the risk of injury, the current study will utilise SJ as an alternative to the DJ. The basic movement and instruction of the jumps are the same with SJ being seven continues jumps. With SJ participants are jumping from a self-selected jump height with each jump different from the other. Stiffness jumps (SJ) can be regarded as a reactive or repeated jump to determine lower body reactive strength. Reactive strength, as an indication of the fast stretch shortening cycle (SSC), can be defined as the ability to change quickly from an eccentric to concentric contraction, which is an important athletic quality for sprinting, acceleration, and changing direction (Stratford, *et al*., 2020).

Hop or continuous rebound tests have recently been proposed to assess lower body reactive strength as an alternative for the DJ. According to Giminiani, *et al*., (2009) a continuous rebound jump, which requires rebounding vertically, is considered an indicator of explosive strength with reactive strength capacities similar to a drop jump. From the hop tests, the Reactive Strength Index (RSI) is calculated by dividing jump height by contact time (Comyns, *et al*., 2019). Chelly and Denis, (2001) found that leg stiffness during a 10-second hopping task had a positive correlation with maximal running velocity in adolescent athletes. Their results, however, did not show a positive correlation between the 10-second hopping task and acceleration, which may have implications in a team environment where short bursts with acceleration is important. In determining the reliability and usefulness of a reactive strength index (RSI) derived from a maximal 5-rebound jump test and a maximal 10-rebound jump test, Comyns, *et al*., (2019) showed that both tests were reliable for the determination of RSI in men and women. The researchers, however, mentioned that the tests were good for the ability to determine a moderate change, but had a concern about the ability of the tests to determine the smallest worthwhile change. Stratford *et al*., (2020) highlighted limitations in the practically use of DJ in an athletic environment, such as the box as required equipment, as well the difficulty with determining actual fall heights during the DJ. The researchers compared the DJ and 10/5 repeated jumps test (RJT) to determine reactive strength index (RSI) and found that the 10/5 RJT had similar RSI values and increased reliability compared to DJ assessments. Stratford, *et al*., (2020), however, warns against using the DJ and RJT interchangeably when athletes are monitored over time because their results indicated that athletes' reactive strength qualities are task dependent.

To perform the stiffness jumps or hops, athletes are instructed to perform seven continuous jumps with extended knees, with their hands-on hips. The aim is to jump as high as possible with a focus being placed on minimising contact time (Arampatzis, *et al*., 2001) where the legs should act like a stiff spring and rebound with minimum delay (Flanagan & Comyns, 2008).

D. FIELD HOCKEY

1. THE GAME

Field hockey is a game played with a hockey stick and a spherical ball. A team consists of a maximum of 11 players taking part at any time during the match. A match is played on a rectangular pitch that is 91.4 m long and 55 m wide (Anon, 2020).

A match consists of four quarters of 15 minutes, an interval of 1 minute between quarter 1 and 2 and between quarter 3 and 4, and a half-time interval of 5 minutes. The team scoring the most goals is the winner. A goal consists of one point. If no goals are scored, or if the teams score an equal number of goals, the match is drawn. A goal is scored when the ball is played within the circle by an attacker and does not travel outside the circle before passing completely over the goal-line and under the crossbar.

2. PHYSICAL DEMANDS

Field hockey is a competitive, high-intensity intermittent team sport with varies physical and technical demands (Lythe & Kilding, 2011; Bartolomei, *et al.*, 2019). It requires high levels of aerobic and anaerobic fitness at any level, however, with technical skills being the most important. A growing number of time motion analysis (TMA) studies have been conducted in team sports making use of global positioning system (GPS) and heart rate monitors to determine the physical demands of the game.

There are a variety of external factors that can influence the physical demand on the player. One of these factors is the surface that the athletes are playing on, such as grass and artificial surfaces. The physical demand of playing hockey on Astroturf was found to be substantially greater (18 %) than playing on grass (Malhotra, Ghosh & Khanna, 1983). Furthermore, the rules of the sport have also been altered, performance analysis techniques and technology have been improved, thereby allowing for greater precision in determining the demands of the game. Recently, GPS technology has been used to determine, amongst others, distance and speed travelled during team sports. Lythe and Kilding, (2011) determined the general and position-specific physical demands and outputs of elite male field hockey players during elite level competition. Firstly, the average distance covered per position was 8 160 ± 428 m in the first half and 6 798 ± 2 009 m in the second half of the match when expressed per player with an average playing time of 51.9 minutes. These distances were lower than previously reported and may be due to the changes in the playing surface and rule changes (Lythe & Kilding, 2011). Field hockey consist of low-speed running (60.9 %) and moderate speed running (33 %), which means 1.9 % of total match time and 6.1 % of total match distance was at intensities greater than 19 $km.h^{-1}$. Like many team sports, hockey is predominantly a low intensity activity, with varying bouts of high intensity activity. As already mentioned, outdoor team sports require greater force capabilities, creating an explosive jump profile (Laffaye, Wagner & Tombleson, 2014). Therefore, suggesting that outdoor sport athletes have the ability to apply force horizontally (running/sprinting) as well as vertically. Even though field hockey is not a “jumping” sport, its performance capabilities may be translated to jump performance.

In a hockey match movement changes were reported every 3.65 seconds which equates to 1148 changes in speed, or 'tempo', during each game (Lythe & Kilding, 2011). These results do not include changes in direction; thus, researchers should not only look distance covered to assess the physical demands of elite hockey matches. Acceleration and deceleration movements as well as backward running and lateral movement utilizes additional energy which increases the physical demands of the sport (Lythe & Kilding, 2011). In addition to this, hockey players are often semi-crouched. Secondly**,** a positional comparison was done, and found that physical demands for most positional groups were similar except for fullbacks, whereby the game demands fullbacks to manage space in the defensive half of the field (Lythe & Kilding, 2011). Even though fullbacks play the longest amount of time, they had the lowest average speed and total distance covered. Fullbacks also reported greater proportion of distance at low intensity and less distance at moderate and high intensities. Physical demands are clearly variable between positional groups in field hockey, however it is presently unknow how these demands translate to the player-specific force-velocity or power-time relationships.

When looking at the abovementioned information, it is clear that field hockey is a sport with varied physical demands, distances covered and bouts of high intensity running. Moreover, field hockey demands sudden changes in direction as well as acceleration and deceleration. Strength and power capabilities are integral to sprint acceleration, specifically over short distances (<20 m) (Nagahara, *et al*., 2014). Nagahara, *et al*., (2014) has shown that a strong correlation exists between sprint performance and CMJ and SQJ results. Due to the semi-crouched nature of the sport, it could be concluded that CMJ could be an ideal jump test for hockey.

E. SUMMARY

In conclusion, power, and the way in which it is generated was discussed. Several physiological factors affect power production and therefore sport performance. Force and velocity have an inverse relationship and may influence sport performance was. Two of the most popular and reliable tests for lower body power are CMJ and SQJ.

A summary of literature underlines the fact that results of research seem to be inconsistent and often contradictory. The lack of standardised testing protocols, variation in sporting background, different equipment for jump testing, power calculations, and large variation in sample sizes are some of the factors leading to inconsistency. Minimal research has been conducted using DJ testing leaving several gaps in jump testing research.

Field hockey is a unique sport with several physical demands. Keeping in mind that hockey is not a jumping sport in its nature, hockey is, however, played in a semi-crouched position. Therefore, one might say that CMJ may be a good test to evaluate lower body power in hockey.

The current study will aim to analyse the difference between force-, power-, velocity-time curve of SQJ and CMJ in university level field hockey player, using SPM analysis. The current study will be using golden standard equipment, athletes from the same sporting background as well as normalising power and force values to body weight.

CHAPTER THREE

METHODOLOGY

A. INTRODUCTION

In this chapter there will be an overview provided of the study design, followed by the recruitment methods for participants, as well as their specific inclusion and exclusion criteria. Thereafter a description of the study outline and the timeline that guided the testing procedures follows, as well as explanations and details regarding the equipment used in the testing and measurements of participants. The statistical analysis of the data obtained closes off the chapter.

B. STUDY DESIGN

The current study followed an observational descriptive study design with no intervention. Experienced, resistance trained male and female hockey players were tested once-off on CMJ, SQJ and SJ during the specific preparatory phase of a hockey season.

C. RECRUITMENT

After consent from the Director of the High-Performance Sport Unit at Stellenbosch University and ethical approval for the study was received, an information session for the first-team players of the hockey club were scheduled at a time as approved by the coaching staff. Only men and women selected for the respective first teams participated, to prevent confounding factors associated with differences in training regimes between different squads. During an information session at the hockey club meeting, the study and testing procedures were explained. All players received a written project information sheet (Appendix A). Players who volunteered to participate completed informed consent forms (Appendix A) prior to the commencement of testing.

D. PARTICIPANTS AND SAMPLING

A purposive sampling method was used in which participants were recruited from the hockey club at Stellenbosch University. Twenty-three university-level field hockey players (n = 10 women and n = 13 men) volunteered to participate in this study. Figure 3.1. presents a flow diagram of the sampling process.

Participants were included if they:

- were registered students at Stellenbosch University.
- were between the ages of 18-25 years.
- were selected for the first men's and women's field hockey teams training squad.
- completed the club's pre-season strength and conditioning programme.
- attended at least 70% of the pre-season gym training sessions.

Participants were excluded if they were:

- were sick or injured at the beginning of the pre-season phase.
- could not complete all jump movements due to any form of impairment (injury or loss of limb).
- failed to attend two of the five familiarisation sessions.

E. RESEARCH PROCEDURES

Once-off testing was completed at the same time of day the players usually had their general training sessions in the gymnasium. All tastings were done in the specific preparatory phase of the hockey season, after players had completed the pre-season strength and conditioning programme in preparation for the competitive season.

Players were required to attend familiarisation sessions that consisted of a five-minute warm-up and three attempts per jump (SQJ, CMJ, SJ). Players that volunteered to participate were required to attend one testing session of about one hour at the Neuromechanics Unit, Central Analytical Facilities (CAF), Stellenbosch University. Players were required to wear appropriate training gear and shoes on the testing day. The researcher was trained in the use of the equipment and software.

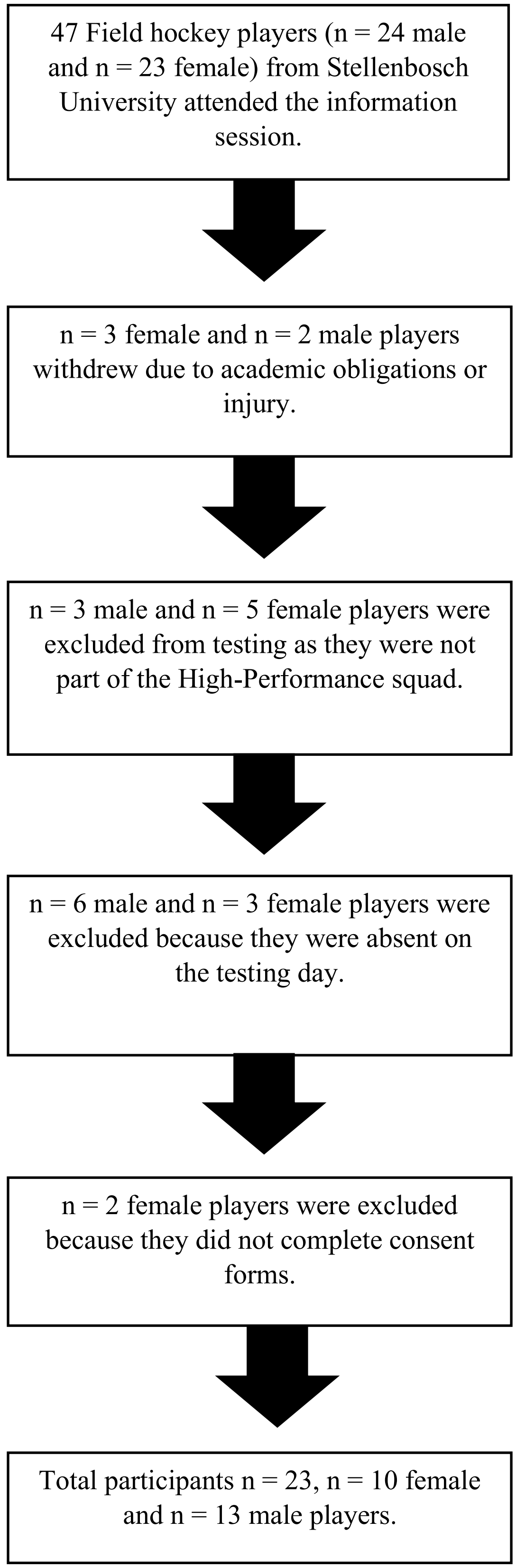

Figure 3.1: Flow diagram of the sampling process.

The researcher was assisted by a trained staff member from the laboratory to perform the testing protocol. Tests were performed in the following sequence, CMJ, SQJ and SJ. The same sequence was followed for each player. The testing protocol performed was deemed to be low risk, as only body weight jumps were performed. Players received their individual force-, velocity- and power-time curves with player-friendly feedback. Results of players who gave their written consent were shared with the strength and conditioning (S&C) coach.

F. ETHICS

The study protocol was approved by the Institutional Research Ethics Committee of the Faculty of Medicine and Health Sciences, as well as the Director of the High-Performance Sport Unit at Stellenbosch University (Ethics reference number: S19/08/152). Players were not tested without signing an informed consent form. The rights and welfare of players were protected. All personal information was kept confidential. The identity of each player was protected by issuing unique numerical codes to the players. Data were stored at CAF Neuromechanics Lab Stellenbosch, on OneDrive. These data were only accessible to the researchers. The study was conducted in accordance with the ethical guidelines and principles of the international Declaration of Helsinki, the South African Guidelines for Good Clinical Practice (2006), the Medical Research Council (MRC) Ethical Guidelines for Research (2002), and the Department of Health Ethics in Health Research: Principles, Processes and Studies (2015) (Appendix B).

G. TESTS AND MEASUREMENTS

Prior to the arrival of players and testing

All communication with players was done through the strength and conditioning coach. Players were informed of the testing day, two weeks in advance. Reminders were given at familiarisation sessions as well as sent on WhatsApp. The CAF Neuromechanics Unit was cleared of any unnecessary equipment on the floor. The force plates were switched on and calibrated by the researcher. The testing room was closed and only one player was allowed in the room at a time.

Anthropometric measurements

Body mass was measured by the researcher with a Bertec instrumented treadmill with embedded force plates (Bertec, Ohio, USA), to the nearest 0.1 kg. The measurement was taken with the players standing completely still on the centre of the force plate with their weight evenly distributed over both feet. This measurement was taken prior to completing the sequence of jumps tested. Measurements were taken with players in their training gear.

During the familiarisation sessions the participants were verbally instructed by the researcher on how to perform the different jump tests, performed a 10-minute dynamic warm-up under supervision for the test session and had three practice attempts for each jump. The researcher is a qualified Sport Scientist with a qualification in High Performance Sport.

Jump tests were performed on a Bertec Instrumented treadmill (Bertec, Ohio, USA) with force being measured at a frequency of 3000 Hz. Mean and peak velocity, force, jump height and rate of force development were calculated from these force data.

Force was measured by the force plates. Power was calculated as seen in the equation below.

$$Power\ (\mathrm{W.kg^{-1}}) = \frac{Work (J)}{Time\ (s)}$$

$$= \frac{Force\ (\mathrm{N.kg^{-1}}) \times Displacement (m)}{Time (s)}$$

$$= Force (\mathrm{N.kg^{-1}})\ \times Velocity (m.s^{-1})$$

**Equation 1: Power* (Haff & Stone, 2015)

Velocity was calculated by integrating acceleration over time, starting with zero velocity at initialization.

$$Velocity(m.s^{-1}) = \frac{\Delta Displacement\ (m)}{\Delta Time\ (s)}$$

**Equation 2: Velocity*

Acceleration was calculated using Newtons Law i.e., F = ma. Force (F) is the net force above or below body mass (body weight in Newtons).

$$Acceleration\ (m.s^{-2}) = \frac{Force(N)}{Mass\ (Kg)}$$

**Equation 3: Acceleration*

RFD was calculated from the slope of the force curve (average slop over a phase of the jump). CMJ slope was measure from the lowest vertical force to zero velocity (eccentric RFD), and SQJ slope was measure from the initiation of the jump to peak force.

For jump height we have two methods, one is using the nett impulse which is calculated using momentum impulse equations (area under the force curve), and the second jump height is calculated using flight time. However, the current study used data from the nett impulse derived jump height.

Participants had to follow specific guidelines and instructions during data collection. Participants were instructed to stand comfortably with both feet on each side of the treadmill (force plate), with their weight evenly distributed on both feet. Before being instructed to jump, participants were asked to stand still for a count of three seconds to determine body mass. On a cue (3, 2, 1, go!) from the researcher, the participants could perform the jump. Each participant performed three attempts of the SQJ and CMJ jump tests and one attempt at the SJ test (Bobbert, *et al*., 1996; Markovic, *et al*., 2004). Three jumps per athlete were recorded. The best of the three jumps (according the maximal jump height) (McMahon, Rej & Comfort, 2017) was used in order to calculate mechanical variables presented in this dissertation. If a player executed a jump incorrectly or lost balance, another jump was performed.

Squat jump*:* A single jump was performed from a self-selected squat depth with hands on hips. No countermovement was allowed. Participants were instructed to jump as high as possible with hands akimbo. Upon landing participants regained balance and after a three second period were instructed to jump again as noted above. As seen in Table 3.1, the following jump data were calculated: jump height (JH), peak power (PP), and peak velocity (PV) was calculated using jump height (Markovic et al., 2004b).

Countermovement jump**:** A single jump was performed standing in a neutral position on the force plate with hand on hips and was instructed to keep their hands on their hips throughout the jump. Participants were instructed to jump as high as possible. Upon initiation participants dipped to a self-selected depth. They were instructed to land with normal flexion of the knee and stand still in a neutral position for three seconds. As seen in Table 3.1, the following jump outcome variables were calculated: jump height (JH), peak power (PP), rate of force development (RFD), and peak velocity (PV) (Markovic et al., 2004b).

Stiffness jump**:** Participants performed seven continuous jumps with knees in full extension and hands akimbo throughout. They were instructed to jump as high as possible and minimise contact time (Arampatzis, *et al*., 2001). All seven jumps data were used during data analysis. As seen in Table 3.1, average jump height (avg JH), peak force (PF) jump data was calculated.

Table 3.1: Summary of variables calculated for each jump test.

Variables	Jump Tests		
	SQJ	CMJ	SJ
Jump height (cm)	X	X	X
Velocity ($m.s^{-1}$)	X	X	
Mean power ($W.kg^{-1}$)	X		
Peak power ($W.kg^{-1}$)	X	X	
Peak force ($N.kg^{-1}$)	X	X	X
Ecc impulse ($N.kg^{-1}$)		X	
Conc impulse ($N.kg^{-1}$)		X	
Ecc time (ms)		X	
Conc time (ms)		X	
Mean RFD ($N.s^{-1}$)	X	X	X
Propulsion time (ms)	X		
Flight time (ms)			X
Contact time (ms)			X

*SQJ= Squat jump, CMJ= Countermovement jump, SJ= Stiffness jump, RFD= rate of force development.

H. STATISTICAL ANALYSIS

Statistical parametric mapping (SPM) analysis was used to analyse force-, velocity-, power-, and displacement time curves. SPM allows researchers to analyse each time-series variable as a single data point. The SPM algorithm calculated the statistic field across the whole curve by correcting the critical test statistic threshold using the smoothness of the data, the data size, and the random field behaviour (Lachlan et al., 2020).

Parametric dependent t-tests were used to determine the differences between CMJ and SQJ performance variables. Pearson correlation was used to investigate the possibility of using SJ-RFD as a performance indicator for CMJ and SQJ. Correlations were interpreted according to the following degrees: strong correlation ($0.50 < r < 1$), medium correlation ($0.30 < r < 0.49$), small correlation (≥ 0.29).

Effect size (ES) calculations (Cohen's d) provided the magnitude of the differences between the two groups as well as specific training phases. Previous research recommended values be defined as follow, trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (McMahon, et al., 2015).

Statistical significance was set at $p < 0.05$.

CHAPTER 4

RESEARCH ARTICLE

Concentric phase characteristics during countermovement and squat jump performance

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*This article has been submitted to the International Journal of Sport Physiology and Performance (**Appendix E**) and is currently under review. This article is included herewith in accordance with the guidelines for authors of this journal. This does not imply that the article has been accepted or will be accepted in the said journal. As a result, the referencing style may differ from other chapters of the thesis (**Appendix F**). The co-authors of the article, Prof Ranel Venter (study leader) and Dr Lara Grobler (co-study leader) hereby give permission to the candidate, Ms Amori van Jaarsveld, to include the article in her thesis.*

CONCENTRIC PHASE CHARACTERISTICS DURING COUNTERMOVEMENT AND SQUAT JUMP PERFORMANCE

Original Investigation

Amori Van Jaarsveld*, Dr Lara Grobler** and Prof Ranel E. Venter*

*Department of Sport Science, Faculty of Medicine and Health Sciences, Stellenbosch University

**Central Analytic Facilities, Neuromechanics Unit, Stellenbosch University

ALL TESTING WAS CONDUCTED IN THE NEUROMECHANICS UNIT, CENTRAL ANALYTIC FACILITIES

(Ethics reference number: S19/08/152).

CORRESPONDING AUTHOR: AMORI VAN JAARSVELD
Stellenbosch University
Mail Address: Suidwal Street
Sport Science Department
Stellenbosch, Western Cape, South Africa
7600
amori@sun.ac.za
+27 21 808 4915

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CONCENTRIC PHASE CHARACTERISTICS DURING COUNTERMOVEMENT AND SQUAT JUMP PERFORMANCE

Abstract

Purpose: Force, power and velocity are some of the primary variables dictating performance in sports. Physiological, neural, and biomechanical mechanisms combine resulting in specific performance outcomes. The aim of the study was to determine the differences in the concentric phase force-, power-, and velocity-time curves of the countermovement jump (CMJ) and the squat jump (SQJ).

Methods: Twenty-three (n = 23) collegiate field hockey players (age = 21 ± 2 years; body mass = 71.2 ± 10.6 kg) volunteered to participate in this study. Each participant performed three attempts of the CMJ and SQJ on a force plate. The best of the three jumps were compared with statistical parameter mapping (SPM). The level of significance was set at $p < 0.05$.

Results: A statistically significant difference was observed between 0 and 40% of the force-time curve for CMJ and SQJ. The velocity-time curve as well as the power-time curve presented a statistically significant difference between 0 to 70%. Significant differences were found in mean and peak force, mean power, jump height and take-off velocity ($p < 0.05$) between CMJ and SQJ. However, no significant difference was found between CMJ and SQJ peak power ($p > 0.05$).

Conclusion: The eccentric phase affected the concentric phase of the CMJ. However, for the latter part (70-100%) of the concentric phase showed no statistically significant differences between CMJ and SQJ. In contrast, analysis on the entire jump showed significant differences between CMJ and SQJ performance variables. Therefore, analysis of phase characteristics may give coaches more insight into specific performance limitations.

Key words: Countermovement jump, Squat jump, Concentric phase, SPM.

INTRODUCTION

Athletic performance is complex with the primary physical characteristics being the ability to generate power, velocity and force[1–4]. Programme design is greatly affected by the assessment of power, velocity, and force. These assessments provide strength and conditioning coaches with insight into the effect of a given programme on an individual[4–6]. Individual strength and power profiles could be determined through assessment of strength and power as well as differentiate between sporting backgrounds[5].

Field hockey is a multidimensional team sport that requires different components for success. Physical fitness testing and analyses of physical demands placed on players during matches have become important components in developing skilled players. Physical demands on players include acceleration, deceleration, backward running, and lateral movement. On average, 1148 changes in speed or tempo have been reported during a field hockey match, these results do not include changes in direction[7]. Strength and power capabilities are integral to sprint acceleration, specifically over short distances (< 20m)[8] as is typically required of field hockey players. Players assume a semi-crouched position for continuous periods during a match, testing players' physical abilities[7]. Field hockey has been described as a lower body dominant sport.

Popular testing methods for lower body strength and power include CMJ and SQJ. Taking the physical demands placed on hockey players into consideration, it has been suggested that CMJ is an ideal test for these types of athletes[4]. CMJ and SQJ are strongly correlated with sprint performance and could therefore determine athletic performance[8]. The CMJ and SQJ have shown themselves to be among the most valid and reliable measures of lower body dynamic strength and power qualities[5,8–11]. In a previous study assessing the reliability and factorial validity of the CMJ and SQJ jump height performance, both CMJ and SQJ displayed good reliability measures of $\alpha = 0.98$ and $\alpha = 0.97$ respectively[10]. CMJ was found to have the higher factorial validity ($r = 0.87$) compared to SQJ ($r = 0.81$)[10]. SQJ has shown to have a small typical error of measurement for SQJ peak force (57.2 N), as well as a smallest worthwhile change of 4.7%[11]. The reliability of calculating SQJ from force-time data utilising the impulse-momentum approach was previously reported[5,6].

Fundamental differences between CMJ and SQJ exist. Regarding the duration of the movement, CMJ (500-1000 milliseconds) takes significantly longer to execute compared to the time of the SQJ (300-430 milliseconds)[12]. The CMJ is performed by standing in an upright neutral position. Initiation of a dip to a self-selected depth is followed by a jump for height [13]. Therefore, during the CMJ an athlete will perform a downward movement (eccentric phase) before jumping from a squat position whereas the eccentric phase is excluded from the SQJ. CMJ provides valuable information about the ability to rapidly produce force utilising the stretch shortening cycle (SSC) to exacerbate the effect[12]. The SQJ is performed from a self-selected squat depth, typically with the thighs parallel to the floor, with no countermovement allowed. Therefore, the SQJ assesses rapid force development from the concentric movement only[12].

Different phases of the CMJ have been described in various ways by researchers. The first description is based on the definition of three phases, namely the unweighted phase, the eccentric phase, where a negative force is seen, and the coupling phase or eccentric-concentric phase during which rate of force development (RFD) is calculated. Peak positive force is reached during the concentric phase whereafter an athlete takes off[14]. The phases of the CMJ have, secondly, been defined based on velocity indicators. The eccentric phase of the CMJ is between peak negative and COM zero velocity. The concentric phase of the CMJ occurred when COM velocity exceeded 0.01 $m.s^{-1}$. Take-off occurred when vertical force was less than 5 times the SD of the body weight[15]. Thirdly, the phases of the CMJ are defined as six distinct phases, namely, the unweighted phase, stretching phase, net impulse phase, propulsion-acceleration I phase, propulsion-acceleration II phase, and propulsion-deceleration phase [16]. It is evident that various descriptions of the CMJ phases exist. This may be due to different calculations/algorithms which may cause confusion and false reporting of data.

Statistical parametric mapping (SPM) has recently become a more frequently used tool for analysis in a sports biomechanics context and has been used for movement analyses in soccer kicking, running, underwater sculling, countermovement jumping, and landing techniques[17–19]. SPM allows researchers to analyse each time-series variable as a single data point[18,19]. It is believed to be a better method of analysing time-series data than curve analysis due to the fact that whole movement analysis can be performed from time-series data[19].

To our knowledge, no research has determined the differences between the concentric phase of the CMJ and SQJ. There is also a lack of research on field hockey players. The first aim of the study was to determine the differences in the concentric phase of the CMJ and SQJ force-, power-, velocity-time curves using SPM analysis. Secondly, the study aimed to compare performance variables for CMJ and SQJ. It is hypothesised that significant differences will be found between the concentric phase force-, power-, velocity-time curves of the CMJ and SQJ. It is also hypothesised that significant differences will be found between CMJ and SQJ performance variables.

METHODS

Experimental approach

A descriptive study method was followed during which hockey players were tested once-off.

Subjects

A purposive sampling method was used. Participants were recruited from the first teams of the hockey club at the institution. Twenty-three (n = 23) collegiate field hockey players (age = 21 ± 2 years; body mass = 71.2 ± 10.6 kg) volunteered to participate in this study.

Only first team players were included in the study to prevent confounding factors associated with different training regimes. Participants partook in the High-Performance Sport training programme, exposing them to periodised resistance training which included CMJ and SQJ. All participants completed informed consent forms. The study was approved by the Director of the High-Performance Sport Unit at the institution. The study was conducted according to the ethical guidelines and principles of the international Declaration of Helsinki and the Department of Health Ethics in Health Research (HREC): principles, processes, and studies.

Procedures

Jump tests were performed on a Bertec Instrumented treadmill (Bertec, USA) at a measurement frequency of 3000 Hz. Data were recorded using Noraxon MR3.14.52 software (Noraxon, USA). The participant's body weight was measured with a Bertec force plate and converted to body mass with accuracy to the nearest 0.1 kg. The participants' age and sex were documented. All tests were conducted in the Neuromechanics Laboratory at the institution.

All participants attended an information session conducted by one of the researchers. During the information session, the scope of the study was explained to the participants, they received a project information sheet, and completed informed consent forms. Although the participants were accustomed to performing the specific jumps, they were required to attend two familiarisation sessions in the laboratory, four weeks prior to testing. Supervised familiarization sessions took place during the "General preparatory" phase of the conditioning program. Participants performed a supervised 10-minute warm-up, whereafter practice jumps were performed.

At the time of testing, each participant performed three attempts of the CMJ and SQJ tests. The best of the three attempts for both jumps was used. Participants were given specific instructions before each jump. They were instructed to stand comfortably on the force plate, with their weight evenly distributed over both feet. Before being instructed to jump, participants were asked to stand still for a count of three seconds to calculate body mass from the force plate data.

Countermovement jump: Participants stood in a neutral position on the force plate with hands on hips. Participants were instructed to jump as high as possible. Upon initiation, participants dipped to a self-selected depth and jumped for height [13]. Upon landing, the participant was instructed to stand still in a neutral position for three seconds before being instructed to jump again.

Squat jump: Participants performed the SQJ jumps from a self-selected squat depth with their hands on their hips. No countermovement action was allowed. Any jump that included a countermovement action leading to a decrease in the ground reaction force that is >20% of body weight before the initiating of the concentric movement phase was excluded from the data analysis. This threshold was based upon the fact that the average decrease in force during the eccentric phase of a CMJ in this group was 70% of body weight. Upon landing participants regained balance and after a three second period were instructed to jump again as noted above. Four players were excluded because all their SQJ had a countermovement with excessive force drop before initiation (> 20% BW).

For this study, the phases of the CMJ (Figure 1) were defined as the initiations, unloading/unweighted phase (from initiation till peak negative force is reached), breaking phase (from peak negative force to peak negative acceleration), eccentric phase (from peak negative velocity to zero velocity), concentric phase (from zero velocity to take-off) and take-off.

[INSERT FIGURE 1]

Statistical Analyses

Statistical parametric mapping (SPM) was used to assess the differences between CMJ and SQJ concentric phase force-, velocity-, power-time curves. The analysis was performed using MATLAB R2020a (Version 9.6). The SPM algorithm calculated the statistic field across the whole curve by correcting the critical test statistic threshold using the smoothness of the data, the data size, and the random field behaviour[20]. The duration of the concentric phase of both the CMJ and

SQJ was normalised to 100% in order to compare the CMJ and SQJ statistically. Therefore, results will be interpreted in percentage value.

SQJ nett impulse calculations were adjusted to detect the stillest point prior to the initiations of the concentric phase. All force and power normalised to force/power generated per body weight.

Parametric dependent t-tests were used to determine the differences between CMJ and SQJ performance variables. Level of significance was set at $p = 0.05$.

[INSERT TABLE 1]

RESULTS

The force-time curve for CMJ and SQJ showed a statistically significant difference (Figure 2) at the initiation of the concentric phase ($p < 0.001$). Force production was statistically significantly greater from CMJ between 0% and 40% compared to SQJ. No statistically significant difference was found for the latter part (41-100%) of the concentric force-time curve.

[INSERT FIGURE 2]

A statistically significant difference was found for most of the velocity-time curve (Figure 3) of the concentric phase (0-75%).

[INSERT FIGURE 3]

Power production was statistically significant higher for CMJ between 0 and 70% of the power-time curve (Figure 4) when compared to SQJ. However, from 71% onwards no significant difference could be seen between CMJ and SQJ.

[INSERT FIGURE 4]

CMJ and SQJ results are recorded in Table 1. The data analysis showed a moderate practically and statistically significant difference ($p < 0.05$) in relative mean force values between CMJ (20.4 ± 2.0 $N.kg^{-1}$) and SQJ (18.4 ± 2.1 $N.kg^{-1}$). A moderate practically and statistically significant difference in relative peak force was also observed between CMJ and SQJ, yielding 25.6 ± 3.0 $N.kg^{-1}$ and 23.0 ± 1.8 $N.kg^{-1}$ respectively ($p < 0.05$).

Take-off velocity of 2.5 ± 0.3 $m.s^{-1}$ for CMJ and 1.1 ± 0.9 $m.s^{-1}$ for SQJ was reported. A significant very large practically and statistically significant difference was found between CMJ and SQJ take-off velocity ($p < 0.05$).

As recorded in Table 1, a very large practically and statistically significant difference in relative mean power was found between CMJ (28.6 ± 4.3 $W.kg^{-1}$) and SQJ (13.3 ± 2.4 $W.kg^{-1}$) ($p< 0.05$). However, a trivial practically difference ($p > 0.05$) was reported in relative peak power between CMJ (49.3 ± 7.9 $W.kg^{-1}$) and SQJ (47.9 ± 8.3 $W.kg^{-1}$).

CMJ and SQJ delivered jump heights of 32.3 ± 6.7 cm and 30.3 ± 6.7 cm, respectively (Table 1). A small practically and statistically significant difference was found between the CMJ and SQJ jump height ($p < 0.05$).

DISCUSSION

As previously mentioned, sport performance is dictated by primary variables which in turn is either affected by physiological, neural, or biomechanical mechanisms. The primary aim of the study was to determine the difference between the concentric phase of the CMJ and SQJ. The secondary aim of the current study was to determine the differences in performance variables for CMJ and SQJ. The primary findings were that the eccentric phase contributes to the differences initially (0-40%) seen when comparing CMJ and SQJ force-, power-, and velocity-time curves. CMJ force production was greater for the first 40% of the concentric phase compared to SQJ. Power and velocity were also great for CMJ for the first 70% of the concentric phase. The secondary finding indicated that CMJ performed statistically significant greater in mean and peak force as well as velocity, jump height and mean power, except for peak power.

The impact of the eccentric phase of the CMJ is visible in the force production upon initiation of the concentric phase (Figure 2). This is furthermore indicated by the statistically significant difference found between CMJ and SQJ force-time curves during 0-40% of the concentric phase of these jumps. A statistically significant difference was found when comparing the velocity-time curve during the concentric phase of the CMJ and SQJ (0- and 75%) (Figure 3). The initiation of the concentric phase is at the moment when the player exceeds zero velocity for both CMJ and SQJ, this is in accordance with phases defined by McMahon, Rej and Comfort (2017). Upon visual inspection it appeared that a steeper slope was present in the initiation of the concentric phase (0 - 40%) for CMJ compared to SQJ. During the initiation of the concentric phase of the CMJ, forces acting on the body are higher than that of SQJ [21]. This is due to the increased downward force created by the eccentric phase of the CMJ. Therefore, in order to overcome these forces greater concentric muscle contraction is necessary for the CMJ. The velocity slope for the eccentric phase of the CMJ shows a linear increase. At the initiation of the SQJ the measured relative force was 1 BW, indicating that the players where still on the force plate at the initiation of the concentric phase. Therefore, players had to overcome body weight from a “semi-seated” position[21], thereby a flatter curve is seen as it takes longer for the body to accelerate upwards.

Moreover, a larger increase in COM velocity during the SQJ is seen during the latter part of the velocity-time curve. Thus, explaining the steeper slope presented by SQJ from 40% onwards. Similarly, power production began at 0 $W.kg^{-1}$ during the concentric phase. A statistically significant difference was found between 0- and 40% of the power-time curve (Figure 4). CMJ showed a linear increase in power as force production was significantly higher for CMJ compared to SQJ during 0 – 40% of the concentric phase and the velocity-time curves showed a linear increase in acceleration. Therefore, resulting in the linear gradient of the power-time curve.

Collectively, a non-significant difference is seen in force-, power-, and velocity-time curves between 76 and 100% of the concentric phase. This could be due to the fact that SPM analysis normalises the duration of the concentric phase of both the CMJ and SQJ to 100%. As previously mentioned, the duration from initiation to take off of the CMJ (500-1000 milliseconds) and SQJ (300-430 milliseconds) are significantly different[12]. The concentric duration for CMJ and SQJ in the current study was 236 – and 325 milliseconds, respectively. This difference in phase duration could lead to peak values in the normalised series occurring at different points in time. Discrete point analysis reported in Table 1, indicated statistically significant differences were recorded for relative mean force between CMJ and SQJ. These findings are in agreement with research reporting greater mean force production during the CMJ compared to the SQJ [22]. Riggs, *et al.,* (2009) stated that the difference between these results are due to the SSC utilisation during CMJ. A statistically significant difference in relative peak force was also observed between CMJ (25.6 ± 2.9 $N.kg^{-1}$) and SQJ (23.0 ± 1.8 $N.kg^{-1}$). These findings are in in agreement with previous literature that indicated similar CMJ measures of relative peak force in college-level team sport athletes (25.8 $N \cdot kg^{-1}$)[23]. A statistically significant difference was found between CMJ (2.5 ± 0.3 $m.s^{-1}$) and SQJ (2.4 ± 0.3 $m.s^{-1}$) take-off velocity. Previous research reported similar take-off velocities for CMJ (2.5 and 2.1 $m.s^{-1}$) and SQJ (2.4 and 2.0 $m.s^{-1}$)[25]. Moreover, relative mean power presented a statistically significant difference between CMJ (28.6 ± 4.3 $W.kg^{-1}$) and SQJ (13.3 ± 2.4 $W.kg^{-1}$). This is in agreement with previous research reporting SQJ mean power of 10.25 $W.kg^{-1}$ for male athletes and 8.1 $W.kg^{-1}$ for female athletes, and CMJ mean power of 28.4 $W.kg^{-1}$ for male athletes and 26.1 $W.kg^{-1}$ for female athletes[22]. However, no statistically significant difference was reported in relative peak power between CMJ (49.3 ± 7.9 $W.kg^{-1}$) and SQJ (47.9 ± 8.3 $W.kg^{-1}$). Additionally, a statistically significant difference was found in jump height between CMJ and SQJ, 32.3 ± 6.7 cm and 30.3 ± 6.7 cm, respectively. These finding are much lower than jump height reported for volleyball players (46.9 and 38.6 cm)[22], sprinters (50cm)[8], baseball (59.1cm) and football (50.1cm)[26] in previous research. These previously reported jump heights are all in athletes participating in plyometric dominant sports and this could be why there is such a discrepancy between the jump heights measured in the current study in comparison to the previous literature. Furthermore, different levels of sports performance were included (elite vs collegiate).

To conclude, only focusing on performance outcomes are not sufficient for individual performance analysis. SPM analysis showed a non-significant difference across all performance variables from

70 – 100%. Therefore, the first recommendation is to investigate the mechanisms of force, power, and velocity production specifically during CMJ and SQJ performance. This may give a coach insight into how athletes achieve performance outcomes and therefore will be able to specifically address certain limitations in performance. As mentioned previously, field hockey is played in a semi-crouched position which may have an impact on force production in the last quarter of a squat movement. Thus, it is recommended that coaches strengthen this portion of the squat in order to improve player force production. To help players to overcome inertia, resistance training with concentric movements only may be beneficial. Furthermore, training of eccentric movements may also improve CMJ performance and therefore improve force production during initiation of the concentric phase of the CMJ. This could, in turn, change the appearance of the power- and velocity-time curves.

PRACTICAL APPLICATION

The current study yielded similar mean and peak force production values as previously reported for collegiate athletes partaking in team sports. Similar findings were reported for power production as well. However, significant differences were found between CMJ and SQJ force-, power-, and velocity-time curves. Analysis of the time curves may show performance limitations that can be corrected through resistance training, for example, eccentric training in order to increase an athlete’s capacity to produce force during the eccentric muscle action. Concentric only resistance training will strengthen SQJ as well as give hockey players strength in the semi-crouched position. Additionally, training in the last quarter of a squat position may be beneficial for hockey players as this is the position, they are in for most of the match.

The current study had the following limitations; Firstly, no kinematic data were collected. Future research could include kinematic data for a comprehensive view of an athlete’s performance. Secondly, the study relied on once-off testing. Longitudinal testing of a periodised training program or an entire competitive season in order to establish whether force- power-, and velocity-time curves can be manipulated by resistance training could be implemented in future research. Thirdly, testing was performed on a single sporting code. Therefore, future research should focus on including other team-sports. Due to sample size limitations, data from men and women were pooled. Research has shown that there are differences between men and women with regards to jump performance. Future research should investigate the differences between male and female team players.

CONCLUSION

Statistically significant differences were observed between the initial portion of the SQJ and CMJ concentric phase force-, power-, and velocity-time curves. Therefore, making the eccentric "advantage" of the CMJ clear. However, a non-statistically significant difference was observed between CMJ and SQJ from 71-100% of the concentric phase. which was supported by discrete variable analysis reporting statistically significant differences between mean and peak force, mean power, take-off velocity and jump height ($p < 0.05$). The authors are of opinion that in-depth analysis of the force-, power-, and velocity-time curves could indicate specific limitations in jump performance and thereby enabling coaches to address the mechanisms of performance outcomes production rather than focussing on the performance outcomes only.

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Table 1: Difference between countermovement jump and squat jump performance.

	CMJ	SQJ				
	Mean±SD	Mean±SD	P	ES	CI	
					Lower	Upper
Mean force (N.kg^{-1})	20.4 ± 2.0	18.4 ± 2.1	P = 0.010	0.95	0.26	1.60
Peak force (N.kg^{-1})	25.6 ± 2.9	23.0 ± 1.8	P = 0.009	1.07	0.37	1.73
Mean power (W.kg^{-1})	28.6 ± 4.3	13.3 ± 2.4	P = 2.04x10^{-13}	4.45	3.19	5.52
Peak power (W.kg^{-1})	49.3 ± 7.9	48.0 ± 8.3	P = 0.119	0.16	-0.48	0.79
Take-off velocity (m.s^{-1})	2.5 ± 0.3	2.4 ± 0.3	P = 0.001	2.13	1.29	2.87
Jump height (cm)	32.3 ± 6.7	30.3 ± 6.7	P = 0.001	0.62	-0.05	1.25

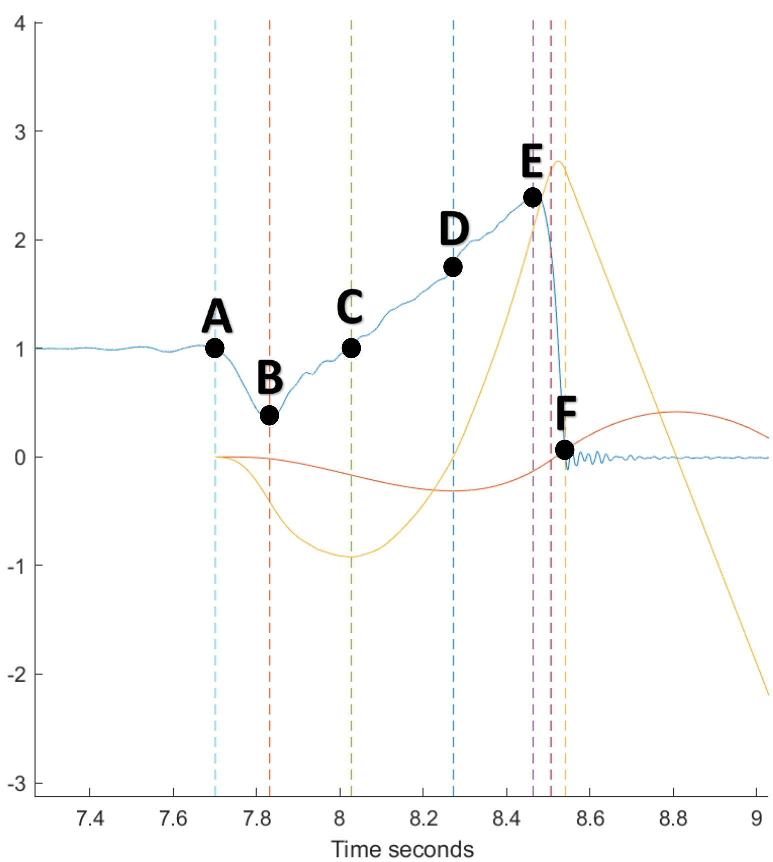

Figure 1: Countermovement jump phases were defined as follows: From point A to B is the unweighted phase. Point B to C is the breaking phase. Point C to D is the eccentric phase. Point D to F is the concentric phase. The solid blue line is the force-time curve. The solid red line is the position curve. The solid orange line is the velocity-time curve.

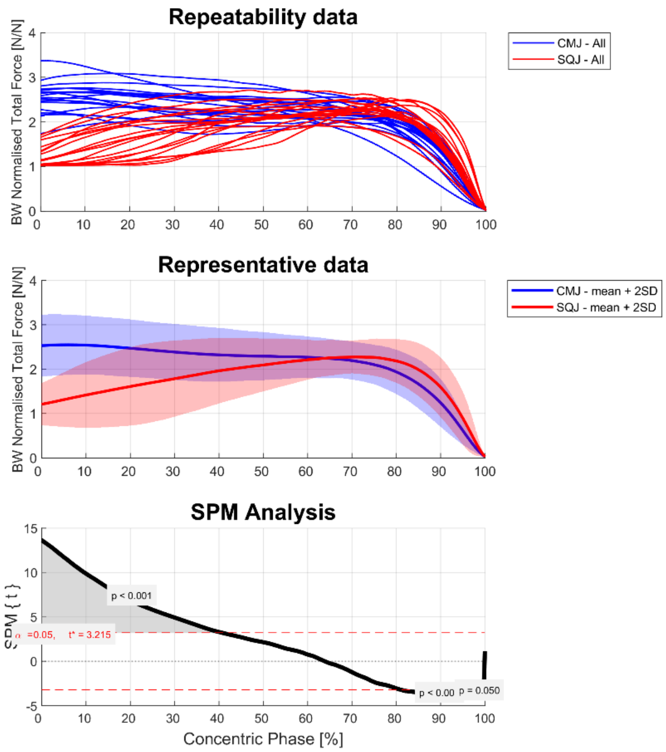

Figure 2: SPM analysis of the force-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph represents individual force-time curves of the concentric phase. The middle graph represented the average force production plotted on the force-time curve for the entire sample. The last graph represents SPM analysis of the force-time curve.

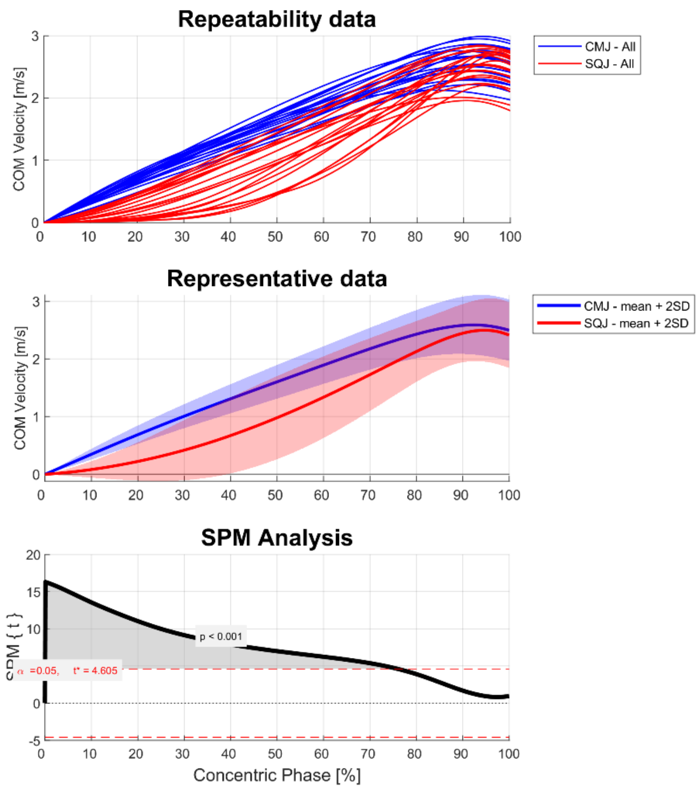

Figure 3: SPM analysis of the velocity-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph characterizes individual velocity-time curves of the concentric phase. The middle graph characterizes the average velocity for the entire sample plotted on the velocity-time curve. The last graph characterizes SPM analysis of the velocity-time curve.

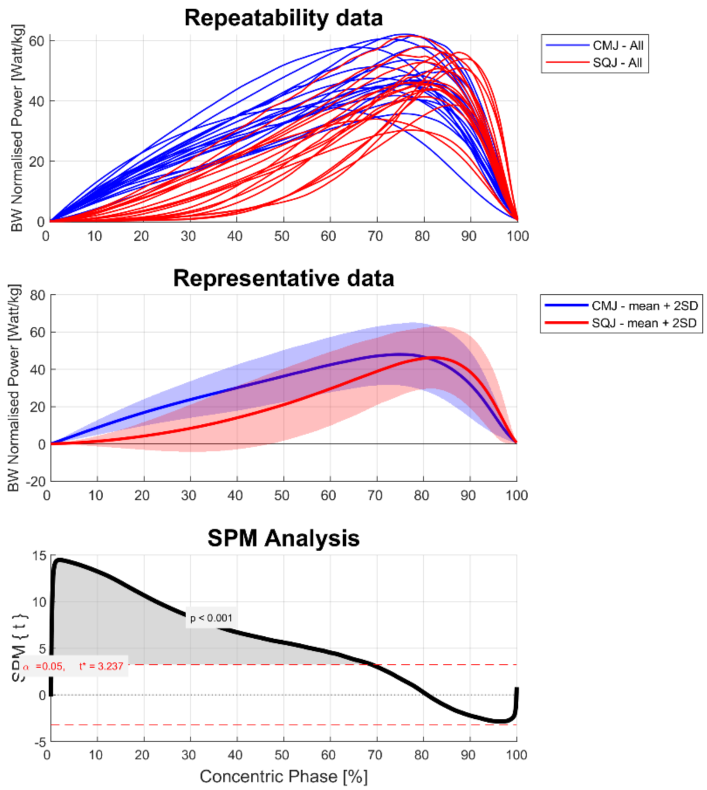

Figure 4: SPM analysis of the power-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph illustrates individual power-time curves. The middle graph illustrates the average power production plotted on the power-time curve. The last graph illustrates SPM analysis of the power-time curve.

CHAPTER 5

CONCLUSION

A. INTRODUCTION

The aim of the study, firstly, was to determine the differences in the concentric phase force-, power-, and velocity-time curves of the countermovement jump (CMJ) and squat jump (SQJ). Secondly, the study aimed to determine the difference in jump height between CMJ and SQJ. Lastly, this study aimed to establish whether stiffness jump (SJ) rate of force development could be used as a performance indicator for CMJ and SQJ jump performance. A group of 23 university-level field hockey players volunteered to participate in the study. The current thesis is presented in article-format. Therefore, the discussion of the primary aim is presented in Chapter 4. Conclusions will be presented during this chapter based on the aims and hypothesis stated in Chapter 1. Furthermore, practical applications, study limitations, and future research opportunities will be identified during this chapter.

1. HYPOTHESIS ONE

It was hypothesised that there would be significant differences between the concentric phase of the CMJ and SQJ force-, power-, velocity-time curves.

The null hypothesis (H_0) stated that no statistically significant differences will be identified between the concentric phase of the CMJ and SQJ force-, power-, and velocity-time curves.

Results indicated a statistically significant difference ($p < 0.001$) between 0- and 40% on the force-time curve for CMJ and SQJ. It was evident that at 0%, CMJ had a significantly higher force production due to the prior eccentric phase. When looking at the velocity-time curve, the significant difference was indicated from 0-75%% of the concentric phase. This is due to the fact that the players needed to overcome the inertia of body weight from a static start during the SQJ, the lack utilisation of SSC, lack of segmental coordination and posture compared to the CMJ. The velocity-time curve presented a statistically significant difference ($p < 0.001$) between 0- and 75%

and a statistically significant difference ($p < 0.001$) was found between 0- and 70% of the power-time curve. Therefore, indicating that no difference was found from 75% onwards. Consequently, the null hypothesis (H_0) was rejected. These results cannot be compared to any previous research due to the novelty of the current study determining the differences between the concentric phases of CMJ and SQJ.

2. HYPOTHESIS TWO

It was hypothesised that a significant difference will be found between CMJ and SQJ jump performance variables. More specifically, the null hypothesis (H_0) stated that no statistically significant difference will be observed between CMJ and SQJ jump performance variables.

Results indicated a significant difference in relative mean- and peak force, take-off velocity, mean power and jump height between CMJ and SQJ ($p < 0.05$). However, no statistically significant difference was found in relative peak power. Similar force, power, and velocity results for CMJ and SQJ were reported by Riggs and Sheppard, (2009). CMJ mean and peak force were similarly reported for college-level team sports athletes. Walsh, *et al.* (2007), reported comparable CMJ take-off velocity although their SQJ take-off velocity was much higher than the current study. Furthermore, previous research is in contrast with the jump height findings of the current study as significantly higher jump heights were reported for team- and individual sports (Laffaye, Wagner & Tombleson, 2014; Nagahara, *et al*., 2014; Riggs & Sheppard, 2009). The differences in jump height may be due to differences in training ages, sporting specific demands and training adaptations. Moreover, research has suggested that the differences between the CMJ and SQJ is largely due to muscle-tendon interactions, residual force, stretch reflex and kinematic differences (Van Hooren & Zolotarjova, 2017). A large emphasis is placed on storage and utilisation of elastic energy and reduction of muscle slack. Earlier studies suggested that elastic energy could be stored in tendinous tissues and utilised in order to increase force production during the upwards phase of the CMJ. Several researchers are of the opinion that this is not the case as only a small amount of energy can be stored during the CMJ and a significant amount of energy will be lost as heat compared to SQJ (Van Hooren & Zolotarjova, 2017). However, the effect of elastic energy storage is largely reliant on the amplitude of the CMJ and the effort exerted (Van Hooren & Zolotarjova, 2017). Reduction of muscle slack and build-up of stimulation plays an important role in explaining the differences between CMJ and SQJ. Jump performance is therefore reliant on stimulation, excitation and contraction dynamics. In a relaxed muscle, fascicles, tendinous tissues and muscle-tendon units may be "slack" (Van Hooren & Zolotarjova, 2017). This slack then needs to be taken up before force can be produced (Van Hooren & Zolotarjova, 2017). It requires up to 100 milliseconds to take up the slack in the muscle. It is therefore, suggested that CMJ performance can be increased by reducing muscle slack.

As mentioned above, when looking at the initiation of the SQJ the only force that needs to be overcome is the force of gravity. However, when initiating the concentric/ upward phase of the CMJ, the body does not only have to overcome the force of gravity but counter the downward momentum of the COM (Van Hooren & Zolotarjova, 2017). Therefore, during the CMJ the muscle-tendon unit and muscle express higher vGRF than compared to the initiation of the SQJ. Research has indicated that during the CMJ tendinous tissues stretch more resulting in higher force production capabilities and tendon stiffness (Van Hooren & Zolotarjova, 2017). Furthermore, it can thus be stated that the countermovement allows the muscle to take up muscle slack whereas with SQJ the effect of muscle slack is reduced (Van Hooren & Zolotarjova, 2017). Another element that needs to be considered is build-up of stimulation. When looking at a team, research has suggested that some individuals build up stimulation slower than others (Van Hooren & Zolotarjova, 2017). Which results in errors in the timing of muscle activation and therefore, may reduce the sensitivity of jump height. Moreover, large differences in CMJ and SQJ performance may not necessarily be a good outcome. It is thus recommended that coaches and practitioners spend time analysing jump test result. For example, poor coordination (i.e., timing of muscle activation as well as muscular coordination) may be result in large differences in CMJ and SQJ. SQJ requires more control and coordination, whereas poor coordination can be masked by build-up of stimulation during CMJ. Field hockey requires players to acceleration, deceleration, backward running, and lateral movement. Furthermore, field hockey players perform up to 1148 changes in speed or tempo during a match (Lythe & Kilding, 2011). Nagahara, *et al*., (2014) stated that strength and power capabilities are integral to sprint acceleration, specifically over short distances (< 20m). Therefore it is recommended to improve coordination as this may improve performance in high intensity situations with limited time to perform a countermovement (Van Hooren & Zolotarjova, 2017). It is also recommended to mimic CMJ and SQJ during training sessions in order to improve the timing of muscle activation. Moreover, it is recommended that athletes perform these jumps under time constraint, unstable loads/ elastic bands or surfaces in order to reduces muscle slack.

Currently, limited research is available comparing the concentric phase of CMJ and SQJ.

In conclusion, four of the six objectives support the rejection of the null hypothesis (H_0) and showed a clear difference between CMJ and SQJ performance variables due to the SSC advantage of the CMJ.

3. HYPOTHESIS THREE

As stated above, the current thesis is in article format. However, results for hypothesis three were not covered in the article presented in Chapter4. Therefore, the results for hypothesis three will be discussed in this section.

It was hypothesised that a strong positive correlation will be found between SJ-RFD and jump performance of CMJ and SQJ.

The null hypothesis (H_0) stated that a negative correlation will be found between SJ-RFD and jump performance of CMJ and SQJ.

Correlations between SJ-RFD and jump performance variables of CMJ and SQJ, were calculated using Microsoft Excel®. Results showed a small correlation between SJ-RFD and CMJ RFD. However, a strong correlation was reported between STJ-RFD and SQJ RFD (r = 0.51) (Table 5.1). As seen in table 5.1 and 5.2, STJ-RFD had a medium correlation with CMJ (r = 0.39) and SQJ (r = 0.44) jump height. Furthermore, small correlations were seen between STJ-RFD for both CMJ (r = -0.01; r = 0.22) and SQJ (r = -0.04; r = -0.02) mean force and power. However, peak mechanical variables delivered mixed correlation results. STJ-RFD had a small correlation with CMJ (r = 0.00) peak force and a medium correlation with SQJ (r = 0.3) peak force. Peak power however, had medium correlations with STJ-RFD for both CMJ (r = 0.31) and SQJ (r = 0.39). Moreover, a medium and small correlation was found between STJ-RFD and take-off velocity of CMJ (r = 0.39) and SQJ (r = -0.14), respectively. Previous literature categorised CMJ and DJ as reactive strength movements, reliant on musculotendinous stiffness and the SSC (Beattie & Flanagan, 2015). Reactive strength movements are further divided into slow and fast SSC. CMJ is a slow SSC movement and therefore has longer movement time and larger angular joint displacement. In contrast, DJ is a fast SSC movement with faster contractions and smaller angular joint displacements (Beattie & Flanagan, 2015). Even though CMJ and DJ are categorised differently, both make use of the SSC. However, the movement patterns of these two jumps are vastly different. Moreover, STJ is the combination of seven continuous jumps (high impact) which would reflect higher vGRF compared to CMJ. An interesting finding in the current study was the strong correlation between STJ-RFD and SQJ-RFD. This was the only strong correlation found between STJ-RFD and the jump performance variables of CMJ and SQJ. The reason for this result could be due to the fact that both STJ and SQJ require the exclusion of a countermovement. Both jumps also require and athlete to rapidly produce force as the movement times are significantly shorter than CMJ. Results from the current study seem to support this hypothesis as stronger correlations were found between STJ-RFD and SQJ mechanical performance variables compared to CMJ. These results may be different if testing is performed on athletes in "jumping" sports.

SJ is commonly used to test reactivity, therefore, it is recommended that more research should be done to determine whether SJ correlates with any performance outcomes such as deceleration, acceleration, and agility.

To conclude, results support the reject of the null hypothesis (H_0).

Retrospective conclusion: In retrospect, RFD seems not have been the most appropriate variable for acute testing of research aim three. Using the SJ as a hop test to determine the Reactive Strength Index (RSI) from jump height and contact time (as mentioned in Chapter Two) may have been a better option in the context of the current study. Also, a further in-depth comparison of the variables between the jumps could add valuable information.

Table 5.1: The correlation between stiffness jump rate of force development and countermovement jump performance variables.

Variables	*SJ RFD*
Jump Height (cm)	0,39*
Mean force ($N.kg^{-1}$)	-0,01
Peak force ($N.kg^{-1}$)	0,00
Mean Power ($W.kg^{-1}$)	0,22
Peak power ($W.kg^{-1}$)	0,31*
CMJ RFD ($N.s^{-1}$)	0,12
Take-off velocity ($m.s^{-1}$)	0,39*

* CMJ= Countermovement jump, SJ= Stiffness jump, RDF=Rate of force development

*Medium correlations between STF-RFD and CMJ variables

Table 5.2: The correlation between stiffness jump rate of force development and squat jump performance variables.

Variables	*SJ RFD*
Jump Height (cm)	0,44*
Mean force ($N.kg^{-1}$)	-0,04
Peak force ($N.kg^{-1}$)	0,30*
Mean Power ($W.kg^{-1}$)	-0,02
Peak power ($W.kg^{-1}$)	0,39*
SQJ RFD ($N.s^{-1}$)	0,51**
Take-off velocity ($m.s^{-1}$)	-0,14

* SQJ= Squat jump, SJ= Stiffness jump, RDF=Rate of force development

*Medium correlations between STF-RFD and SQJ variable**Strong correlation between STJ-RFD and SQJ RFD

B. SUMMARY OF THE OUTCOME OF THE STUDY

Table 5.3 shows a summary of the outcome of the study, based on the stated hypotheses and variables assessed.

Table 5.3: Summary of hypotheses and outcomes based on the variables assessed.

Hypotheses	Variables			
	Accepted	Outcomes	Rejected	Outcomes
1. The null hypothesis (H_0) stated a no significant difference will be identified between the concentric phase of the CMJ and SQJ force-, power-, velocity-time curves. Rejected.			Statistically significant differences were between CMJ and SQJ force-, power-, velocity-time curves.	$P < 0.05$
2. The null hypothesis (H_0) stated that no significant difference will be observed between CMJ and SQJ jump performance variables. Rejected.	Peak power and jump height.	$P < 0.05$	Mean force and power, take-ff velocity, and peak force.	$P < 0.05$
3. The null hypothesis (H_0) stated that no correlation will be found between SJ-RFD and jump performance of CMJ and SQJ. Accepted.			SJ RFD, jump height, mean and peak force, mean and peak power, SQJ RFD, Take-off velocity	Small and medium correlations were found for CMJ variables. Small to strong correlations were seen for SQJ variables.

C. PRACTICAL APPLICATION

The current study yielded similar mean and peak force production values as previously reported for collegiate-level athletes partaking in team sports. Similar findings were also reported for power production. However, significant differences were found between CMJ and SQJ force-, power-, and velocity-time curves. Therefore, SPM analysis may offer coaches with a comprehensive view of a team's performance. The analysis of time curves may thus show performance limitations that could potentially be corrected through resistance training. For example, eccentric training is recommended in order to enable athletes to produce more force during the eccentric phase and in turn increase CMJ performance, which in turn may change the appearance of the power- and velocity-time curves. In order to change the gradient of the SQJ velocity-time curve, concentric only resistance training could strengthen hockey players in the semi-crouched position as well as enable the players to overcome inertia at a faster rate. The semi-crouched position that field hockey is played in may have an influence on force production in the last quarter of a squat movement. Thus, training in the last quarter of a squat position may be beneficial for hockey players are regularly in that position.

D. STUDY LIMITATIONS

The first limitation of the current study is that due to the SARS-CoV2 (Covid-19) pandemic, adjustments needed to be made to the aims, objectives and hypothesis. Therefore, the study relied on once-off testing instead of following the original longitudinal research plan. In retrospect RFD would not have been the right variable for acute testing of research aim three. Secondly, the current study collected no kinematic data. Thirdly, testing was performed on a single sporting code. Fourthly, it can be argued that field hockey is not a "jumping" sport. Lastly, male and female data were pooled. Research has shown that there are differences between male and female athletes skeletal muscle kinetics, hormones, and muscle fibre-type composition (Haizlip, Harrison & Leinwand, 2015). Women have more slow-twitch muscles fibres compared to men, which may lead to a decrease in contractile velocity in women (Haizlip, Harrison & Leinwand, 2015). Therefore, future research should analyse male and female data separately, using SPM.

E. RESEARCH RECOMMENDATIONS

Future research should include SPM analysis for a comprehensive view of athletes' performance. Thereafter, inclusion of the mechanisms of force, power and velocity production should be investigated when determining CMJ and SQJ performance. Future research should include longitudinal testing of a periodised training program or an entire competitive season in order to establish whether force- power-, and velocity-time curves can be manipulated by resistance training. Furthermore, other sporting codes should be included in future research, as well as team- and individual sports. Moreover, future research should test the reliability of STJ. Future research should also investigate whether other STJ variables indicate moderate to strong correlations with CMJ and SQJ jump performance variables.

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Appendices

A. Appendix A - *Informed Consent Form*

STELLENBOSCH UNIVERSITY

CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT(S):	UNIVERSITEIT STELLENBOSCH UNIVERSITY
Force and velocity jump profiles of university-level field hockey players during of a competitive season	
DETAILS OF PRINCIPAL INVESTIGATORS (PIs):	
Title, first name, surname: **Amori van Jaarsveld** (MSc in Sport Science) under the supervision of **Prof R. E. Venter and Dr L Grobler**	**Ethics reference number:** S19/08/152
Full postal address:	**PIs' Contact numbers:** **073 062 7880**

PARTICIPANT INFORMATION LEAFLET AND CONSENT FORM

We would like to invite you to take part in project at the Department of Sport Science, Stellenbosch University. Please take some time to read the information presented here, which will explain the details of this project. Please ask the study PIs or supervisor/ co-supervisor any questions about any part of this project that you do not fully understand. It is very important that you are completely satisfied that you clearly understand what this research entails and how you could be involved. Also, your participation is **entirely voluntary,** and you are free to decline to participate. In other words, you may choose to take part, or you may choose not to take part. Nothing bad will come of it if you say no: it will not affect you negatively in any way whatsoever. Refusal to participate will involve no penalty or loss of benefits or reduction in the level of care to which you are otherwise entitled to. You are also free to withdraw from the study at any point, even if you do agree to take part initially.

This study has been approved by the Health Research Ethics Committee at Stellenbosch University. The study will be conducted according to the ethical guidelines and principles of the international Declaration of Helsinki, the South African Guidelines for Good Clinical Practice (2006), the Medical Research Council (MRC) Ethical Guidelines for Research (2002), and the Department of Health Ethics in Health Research: Principles, Processes and Studies (2015).

What is the research study about?

All the testing will be hosted by the Department of Sport Science, Stellenbosch University and will take place at the Neuromechanics unit within the Central Analytical facilities (CAF) laboratory which is situated at Coetzenberg behind Maties Gymnasium. The total amount of participants needed for this study is 14 females and 14 males, with all participants required to complete the testing at the Neuromechanics unit.

Why do we invite you to participate?

You were selected as a possible participant in this study because you are a healthy field hockey player and completed pre-season club strength and conditioning programme.

This study will aim to determine:

The pre-competition force and velocity jump profiles of university-level field hockey players for squat jump, countermovement jump, isometric mid-thigh pull, 5-countermovement jump and stiffness jump.

Changes in the force and velocity jump profiles of university-level field hockey players during three different phases of a strength and conditioning program of one competitive season, namely strength, strength-speed, and speed-speed endurance phases.

Differences in the force-velocity jump profiles between university-level male and female field hockey players for squat jump, countermovement jump, isometric mid-thigh pull, 5-countermovement jump and stiffness jump.

What will your responsibilities be?

Testing

The following tests will be performed during a strength phase (14 January - 18 February), a strength-speed phase (18 February -15 April) and speed-speed endurance phase (01 April – 24 June) of one competitive season. All the tests will be done on one day for the training phase. The test will be between 14 January 2020 and 24 June 2020. You will be informed of the specific testing dates two weeks in advance. You will be required to attend two of three familiarisation sessions, where you will be instructed on how to perform the jumps, warm-up and practice the jumps. Familiarisation sessions will take place during the first week of pre-season. Optojump (optical measurement system) will be used during the familiarisation sessions as it is portable. Upon the third session, baseline testing will be done.

You will be instructed to perform the tests in the following way:

Squat jump: a single jump will be performed from a self-selected squat depth with hands on hips. No countermovement will be allowed.

Countermovement jump: Participants will perform a single jump starting with hands on their hips and standing in a neutral position. With knee flexion before take-off, participants will be instructed to jump as high as they can. They need to land with normal flexion of the knee and stand still in a neutral position for 2 seconds.

5-Countermovement jump: Participant will perform 5 consecutive countermovement jumps without stopping. Hands will be kept on the hips.

Isometric mid-thigh pull: The mid-thigh position will be determined for each participant by marking the mid-point distance between the knee and hip joints. Each participant will self-select their hip and knee angles by assuming their preferred deadlift position. The height of the barbell was adjusted to stay in contact with the mid-thigh. The participants were allowed to us overhand, mixed, or hook grip. The participants will be instructed to pull upward on the barbell as hard and as fast as possible with continued maximal effort for 6 seconds. No pre-contraction will be allowed (Wang, *et al., 2016)*

Stiffness jump: Participant will perform 7 continues jumps with straight/extended knees and hands on hips. They will be instructed to jump as high as they can (Arampatzis, *et al*., 2001).

Will you benefit from taking part in this research?

You will not directly gain benefit from participation in the short term. You will receive player-friendly feedback regarding your own jump profile. Should you give written consent, your strength and conditioning coach could get access to your testing results at the end of the season to enable him/her to design a player-specific program for the next season. The testing data from this study could be applied to periodization of a training program. Training programs can easily be individualized. It is a way of monitoring athletes and making sure that they are not over trained neither undertrained. Monitoring and adapting individual training programs will allow a peak in athletic performance at the right time.

Are there any risks involved in your taking part in this research?

There will be no serious risks involved in the study. The potential risks will be minimised as much as possible by thoroughly explaining the procedure to you and carefully monitoring all the test and training sessions. All measurements are **within your health and fitness capacity.** If an injury or adverse event occurs, the test will be terminated immediately, and you will receive specific supervision from the researcher who is qualified to perform basic medical aid. There will always be a basic life support (BLS) qualified healthcare professional available to perform cardiopulmonary resuscitation (CPR). Should any emergency arise, you will be stabilized and then immediately transported to the emergency room at Stellenbosch Medi-Clinic.

If you do not agree to take part, what alternatives do you have?

You can choose whether to take part in this study or not. If you volunteer to participate in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you do not want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrants doing so. Participation will be discontinued if you fail to comply with the testing protocol. Your consent to participate in this research will be indicated by your signing and dating of the consent form.

Even though it is unlikely, what will happen if you get injured somehow because you took part in this research study?

Stellenbosch University has insurance to cover participants in all non-industry sponsored research studies that are registered with the HREC. Stellenbosch University is covered by comprehensive debt-free insurance and will pay any medical costs incurred by people participating in this project (whether they used the medication for this trial or if they participated in another way). Debtless insurance means you do not have to prove that the sponsor (the University) owes you to the events that caused the charges to you.

Will you be paid to take part in this study and are there any costs involved?

As a participant, you will not receive any financial reimbursement or payment to participate in the study. Participation in this study will not have financial implications for you.

Is there anything else that you should know or do?

You will receive a copy of this information and consent form for you to keep safe.

Future use of results:

Your data will be safely stored for a period of six years. During this time your analysed data will be used for publications/conference presentations. Only group results will be reported, and it will not be possible to identify you as an individual player. All information obtained in the study will not be disclosed, unless published, in which case it will be treated as not to identify anyone. I might want to do further analyses of the data collected upon the completion of the current study. Results of the current study will only be used in the same field of study.

Confidentiality

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of withholding the names of the participants and only using numerical codes to represent subjects. This means that the reported results will only include codes and no names at all. Recorded data will be filed and stored on one-drive and on a password protected computer and will only be accessed by the researcher and study supervisors. All information obtained in the study will not be disclosed, unless published, in which case it will be treated as not to identify anyone. The reported results will only be shared with the strength and conditioning coach if you give written consent. If I should do further analyses of the data collected, the same numerical codes as used in the current study will still apply. It will ensure that data are anonymous. All results obtained will not be disclosed, unless published, in which case it will be treated as not to identify anyone.

Declaration by participant

By signing below, I ………………………………..…………. agree to take part in a research study entitled: Force and velocity jump profiles of university-level field hockey players during a competitive season.

I declare that:

I have read this information and consent form, or it was read to me, and it is written in a language in which I am fluent and with which I am comfortable.

I have had a chance to ask questions and I am satisfied that all my questions have been answered.

I understand that taking part in this study is **voluntary,** and I have not been pressurised to take part.

I may choose to leave the study at any time and nothing bad will come of it – I will not be penalised or prejudiced in any way.

I may be asked to leave the study before it has finished, if the study doctor or researcher feels it is in my best interests, or if I do not follow the study plan that we have agreed on.

My data may be safely stored for future use in research reports.

Signed at (*place*) ....…........…………….. on (*date*) …………....……….. 2020

____________________ _________________

Signature of participant Signature of witness

My results may be shared with the strength and conditioning coach of the hockey team.

YES _______ NO _____

Declaration by investigator

I *(name)* …………………………………………..……… declare that:

I explained the information in this document in a simple and clear manner to …………………………………..

I encouraged him/her to ask questions and took enough time to answer them.

I am satisfied that he/she completely understands all aspects of the research, as discussed above.

I did/did not use an interpreter. (*If an interpreter is used then the interpreter must sign the declaration below.)*

Signed at (*place*) ....…........…………….. on (*date*) …………....……….. 2020.

Signature of investigator

Signature of witness

B. Appendix B – *Ethical Approval Letter*

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

Approval Notice

New Application

11/12/2019

Project ID : 10913

HREC Reference No: S19/08/152

Project Title: FORCE AND VELOCITY JUMP PROFILE FOR UNIVERSITY-LEVEL FIELD HOCKEY PLAYERS DURING A COMPETITIVE SEASON

Dear Ms. Amori Van Jaarsveld,

The Response to Modifications received on 10/12/2019 09:28 was reviewed by members of **Health Research Ethics Committee 2 (HREC2)** on 11/12/2019 and was approved.

Please note the following information about your approved research protocol:

Protocol Approval Date: 11 December 2019

Protocol Expiry Date: 10 December 2020

Please remember to use your Project ID **[10913]** and Ethics Reference Number **[S19/08/152]** on any documents or correspondence with the HREC concerning your research protocol.

Please note that the HREC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

After Ethical Review

Please note you can submit your progress report through the online ethics application process, available at: Links Application Form Direct Link and the application should be submitted to the HREC before the year has expired. Please see *Forms and Instructions* on our HREC website (www.sun.ac.za/healthresearchethics) for guidance on how to submit a progress report.

The HREC will then consider the continuation of the project for a further year (if necessary). Annually a number of projects may be selected randomly for an external audit.

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We wish you the best as you conduct your research.

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If you have any questions or need further assistance, please contact the HREC office at 021 938 9677.

Yours sincerely,

Mr. Francis Masiye,

HREC Coordinator,

Health Research Ethics Committee 2 (HREC2).

Page 1 of 2

C. Appendix C – *Statistical parametric mapping (SPM) figures*

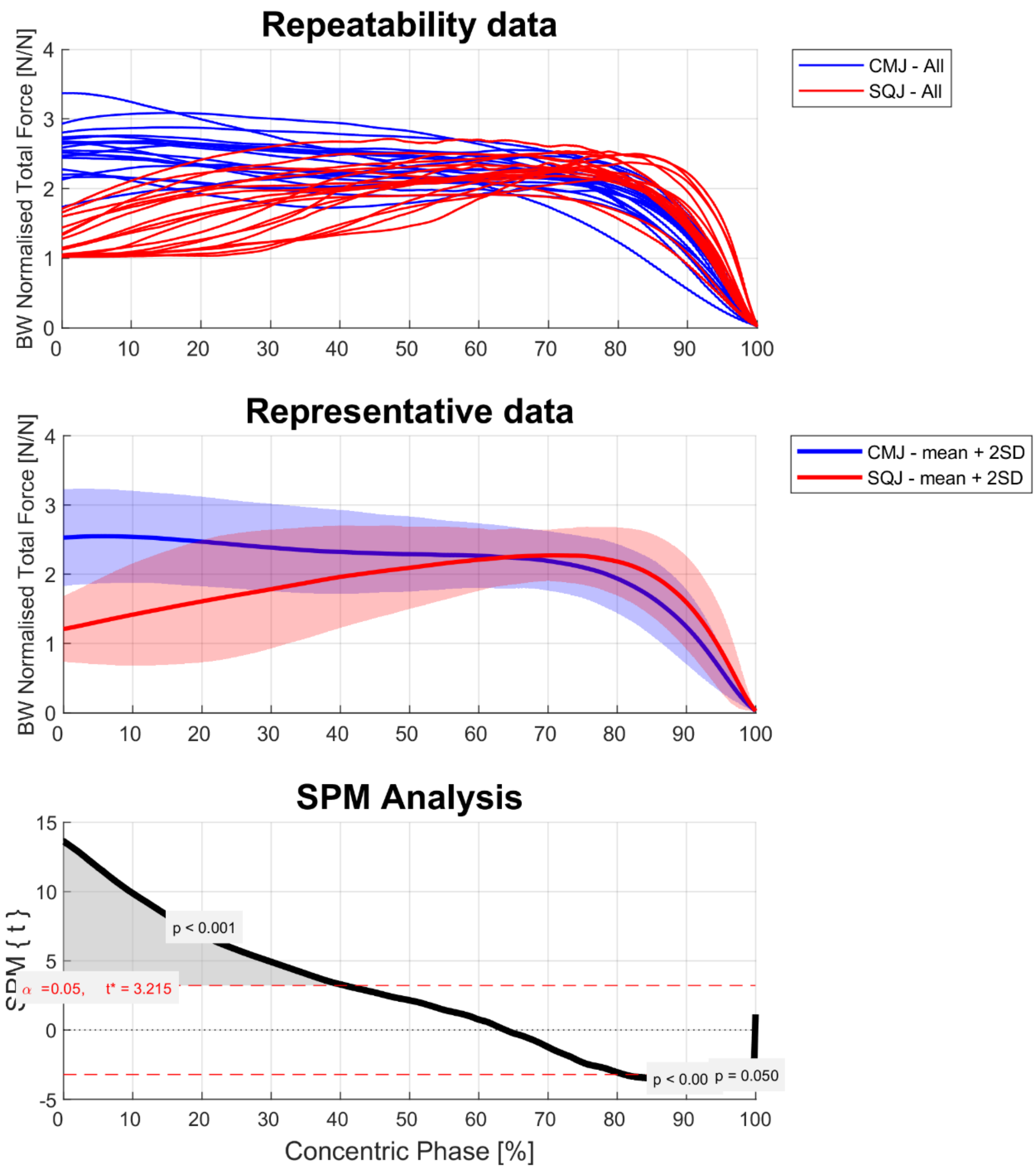


Figure 1: SPM analysis of the force-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph represents individual force-time curves of the concentric phase. The middle graph represented the average force production plotted on the force-time curve for the entire sample. The last graph represents SPM analysis of the force-time curve.

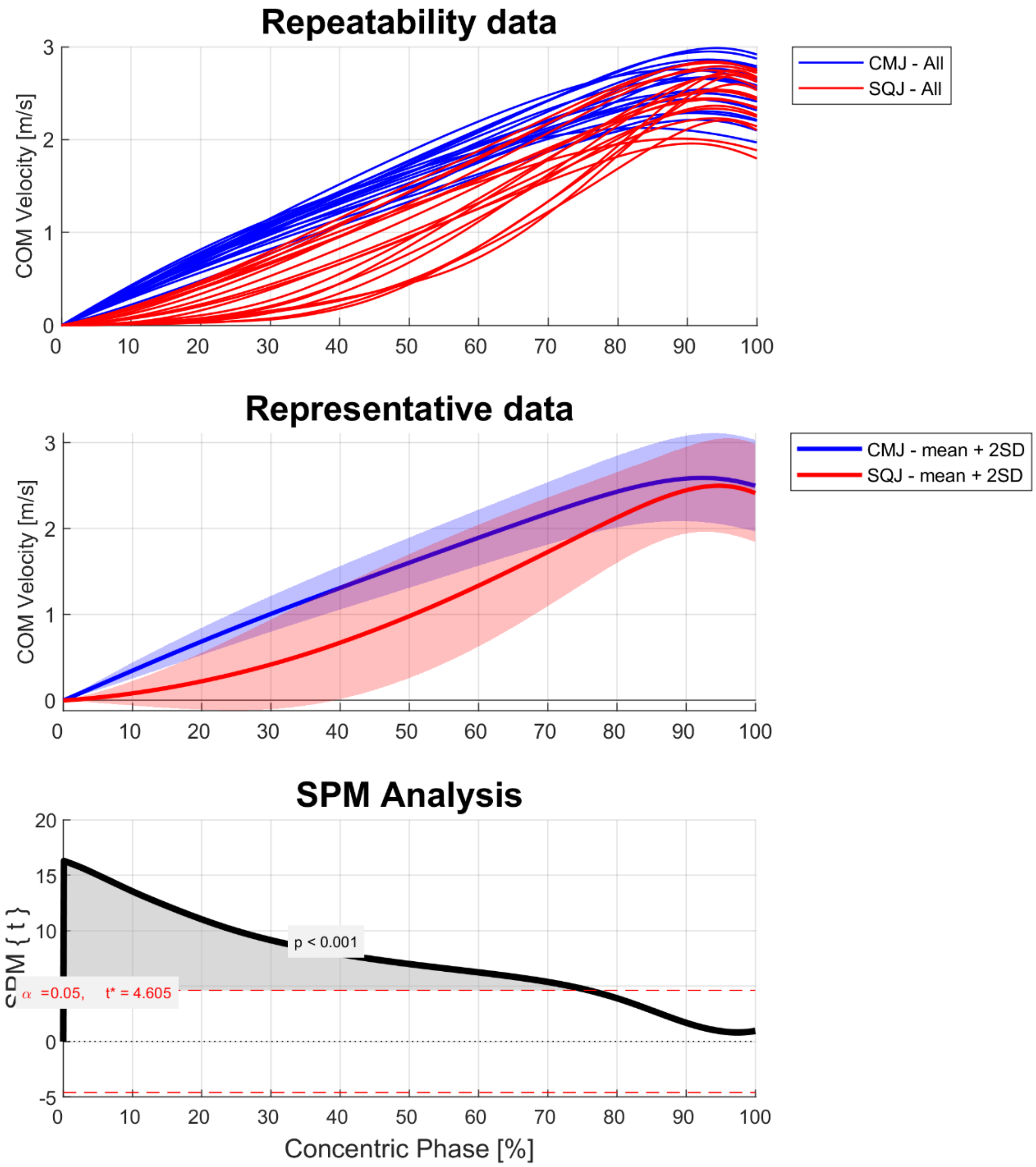


Figure 2: SPM analysis of the velocity-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph characterizes individual velocity-time curves of the concentric phase. The middle graph characterizes the average velocity for the entire sample plotted on the velocity-time curve. The last graph characterizes SPM analysis of the velocity-time curve.

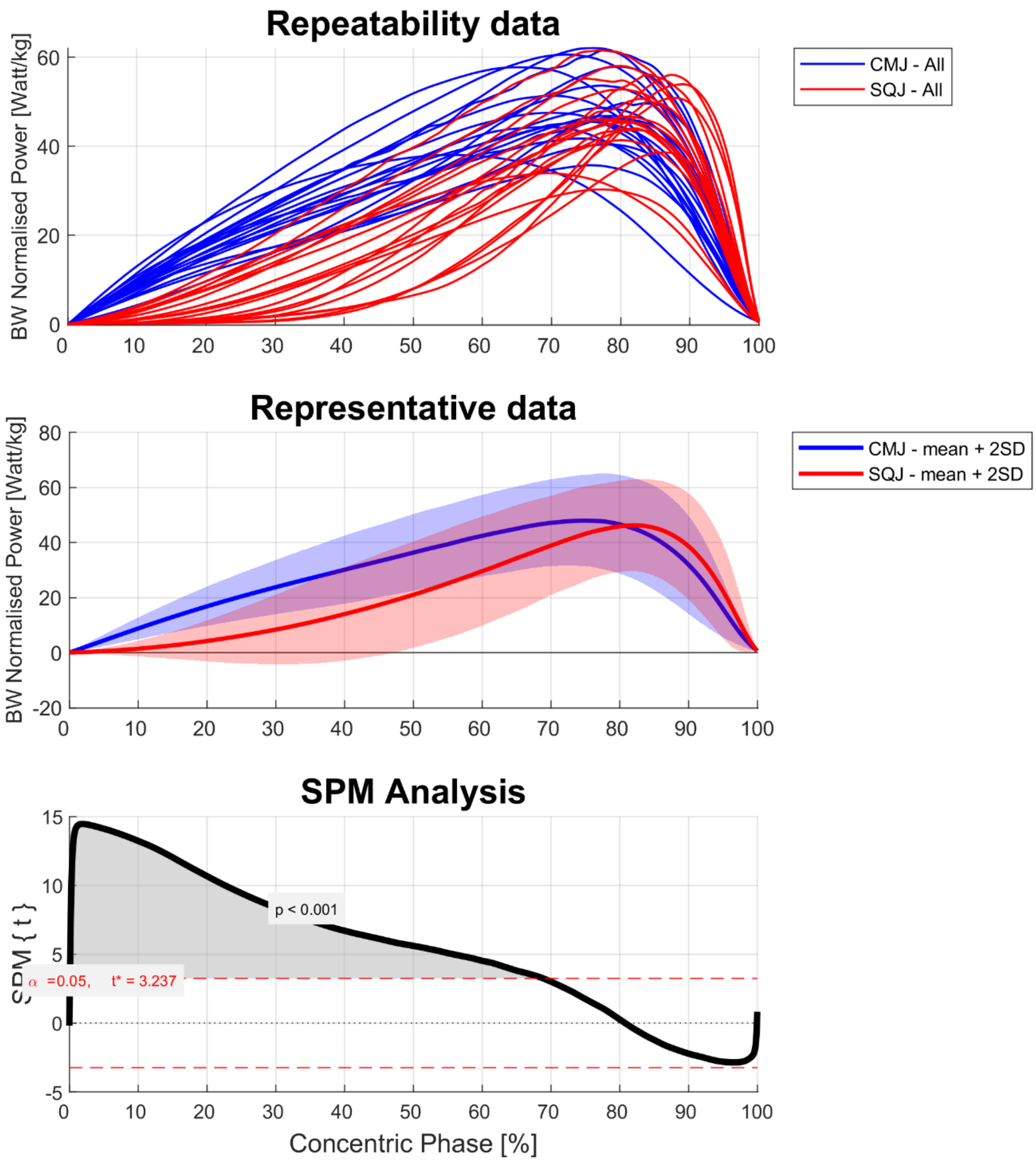


Figure 3: SPM analysis of the power-time curve of the concentric phase of the countermovement jump, and the squat jump. The top graph illustrates individual power-time curves. The middle graph illustrates the average power production plotted on the power-time curve. The last graph illustrates SPM analysis of the power-time curve.

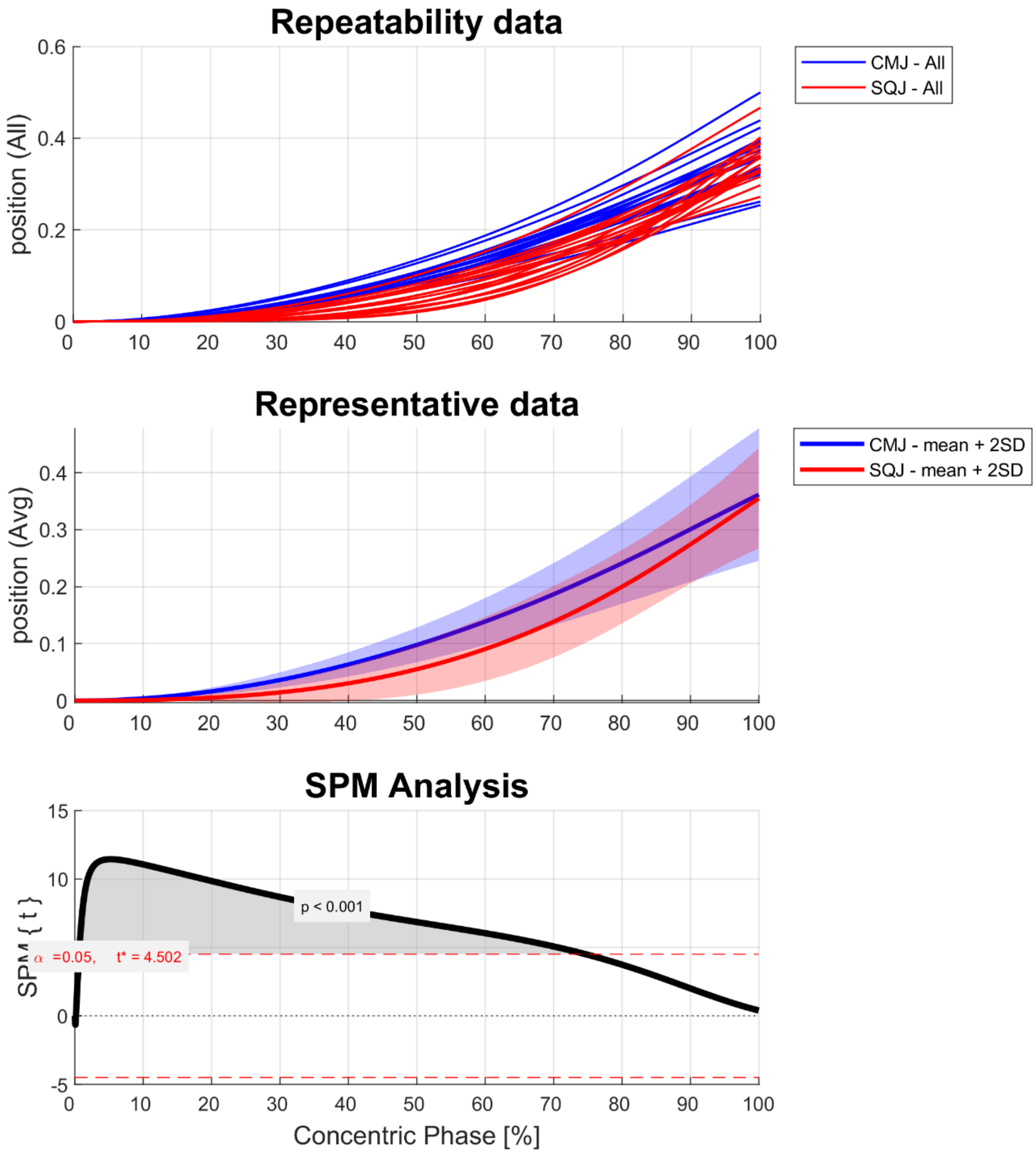
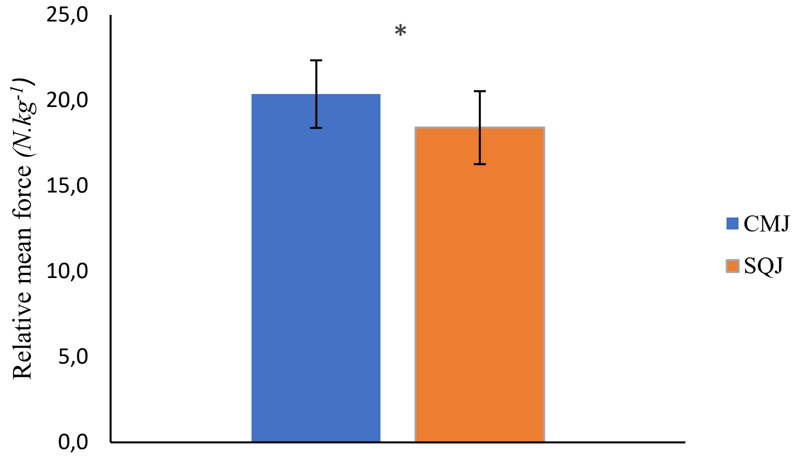


Figure 4: SPM analysis of the position-time curve. The top graph illustrates individual position-time curves. The middle graph illustrates the position during the concentric phase of the CMJ and SQJ. The last graph illustrates SPM analysis of the position-time curve.

D. Appendix D – *Descriptive data analysis figures*



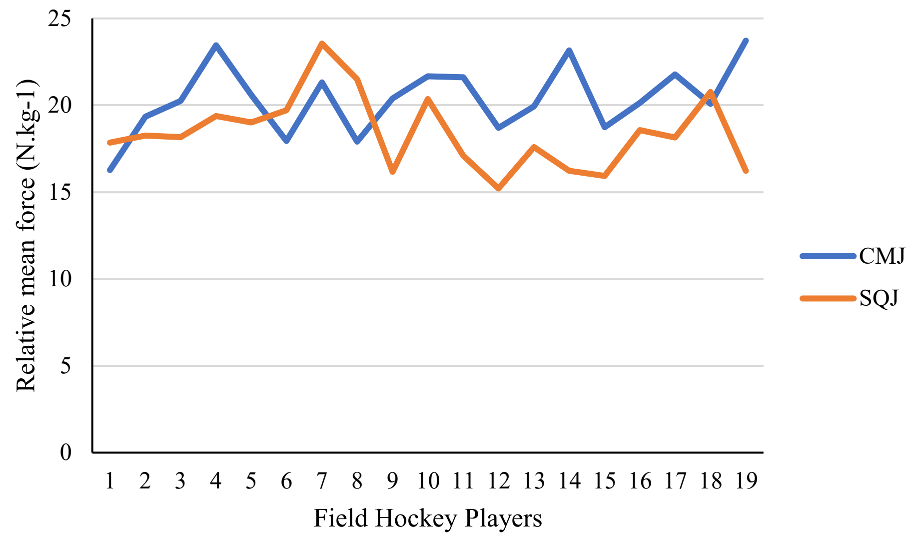


Figure 1: The difference between countermovement jump and squat jump relative mean force (p=0.01)

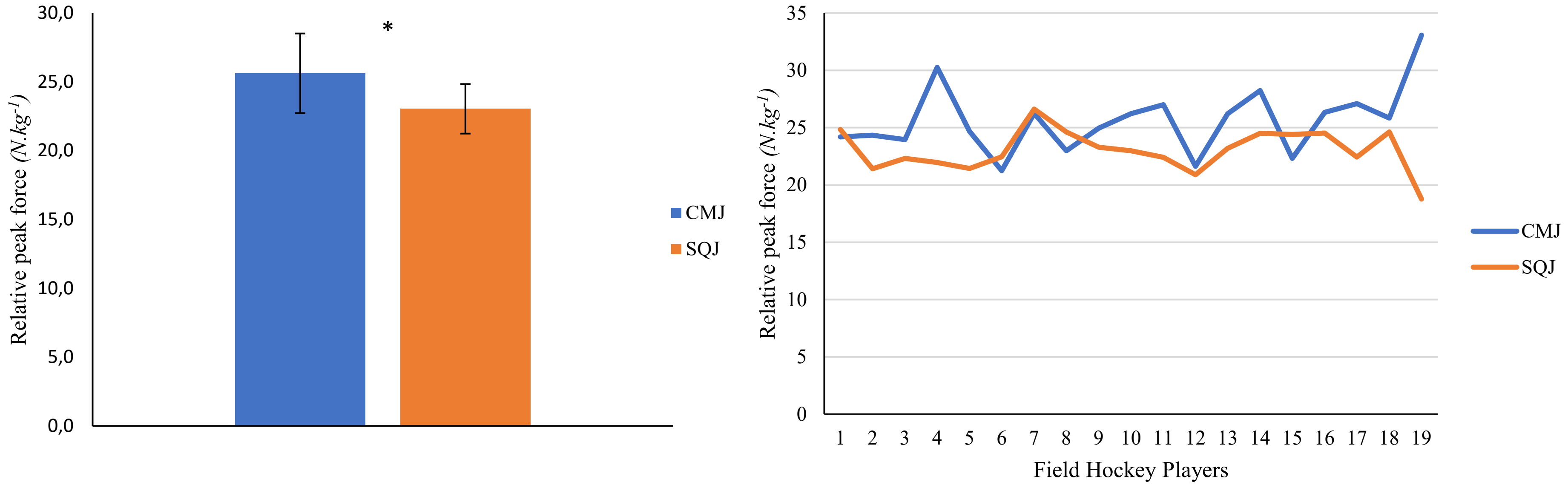


Figure 2: The difference between countermovement jump and squat jump relative peak force (p=0.009)

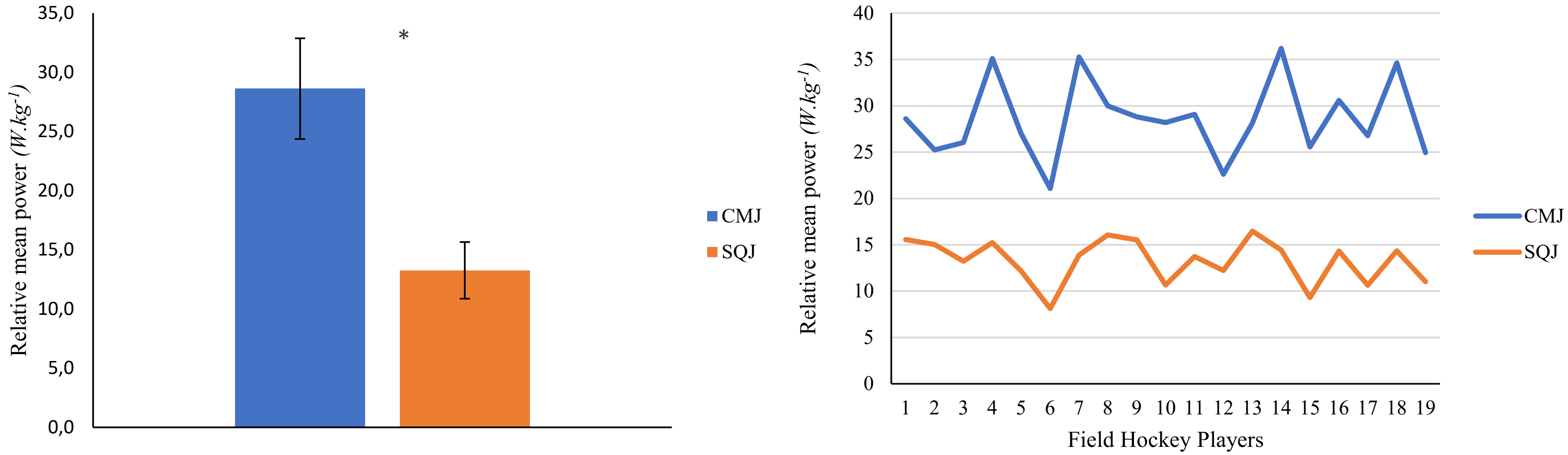
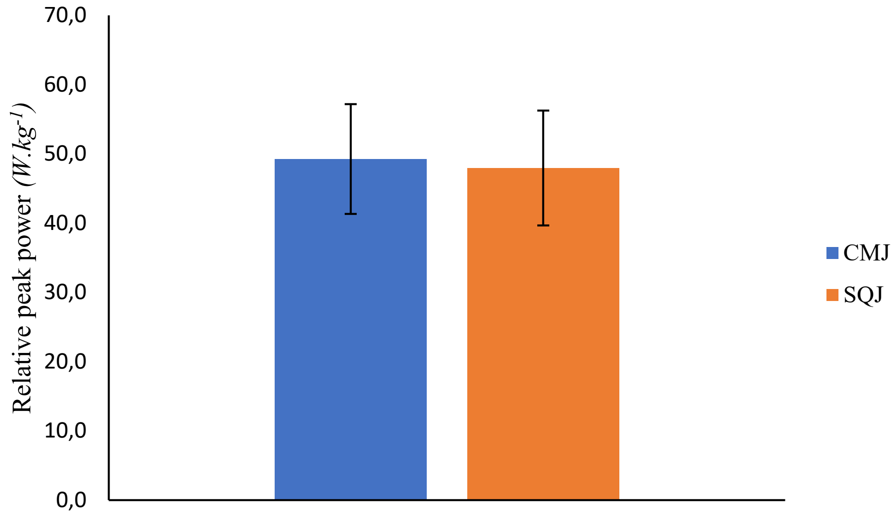


Figure 3: Countermovement jump and squat jump relative mean power (p=2.04E-13)



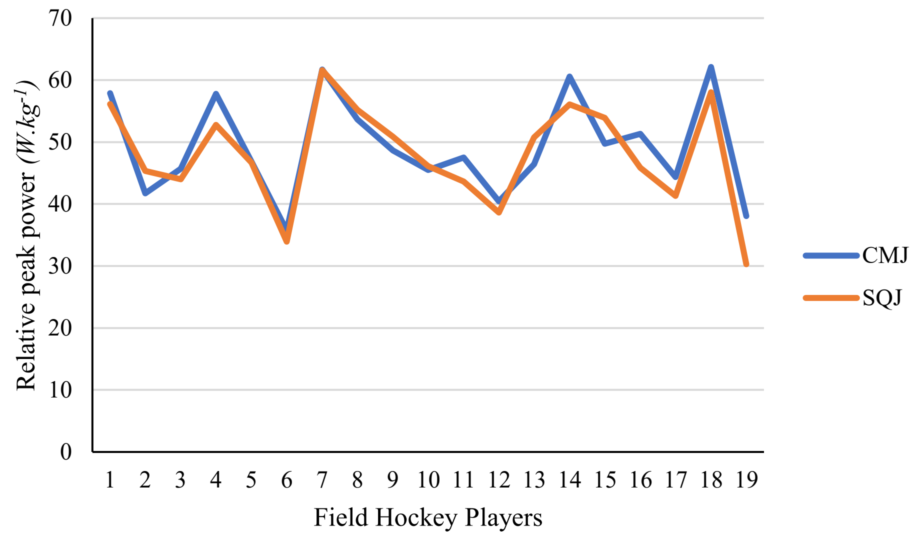
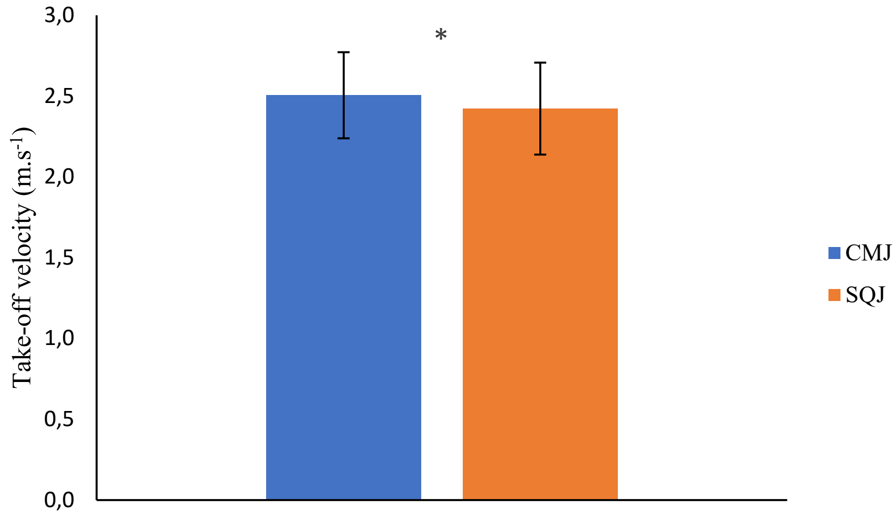


Figure 4: Countermovement jump and squat jump relative peak power (p=0.12)



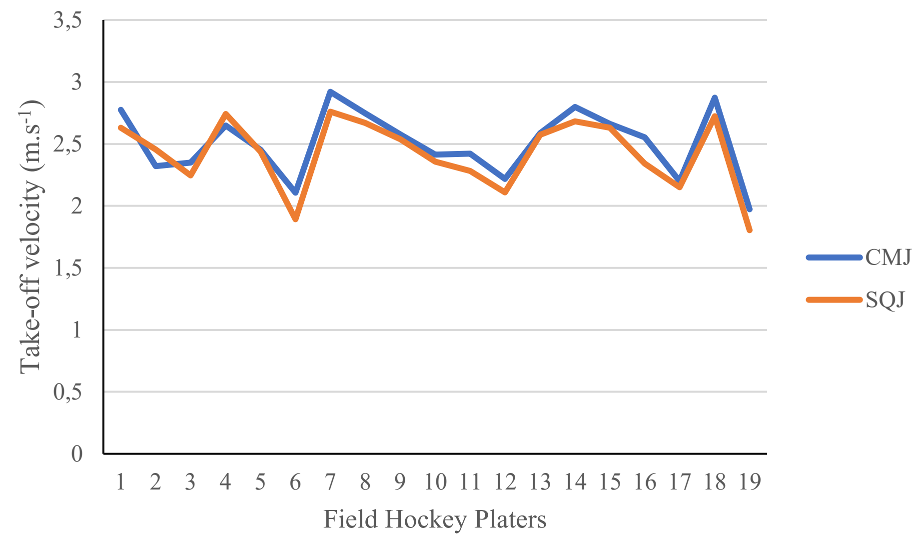


Figure 5: Take-off velocity for countermovement jump and squat jump (p=0.001)

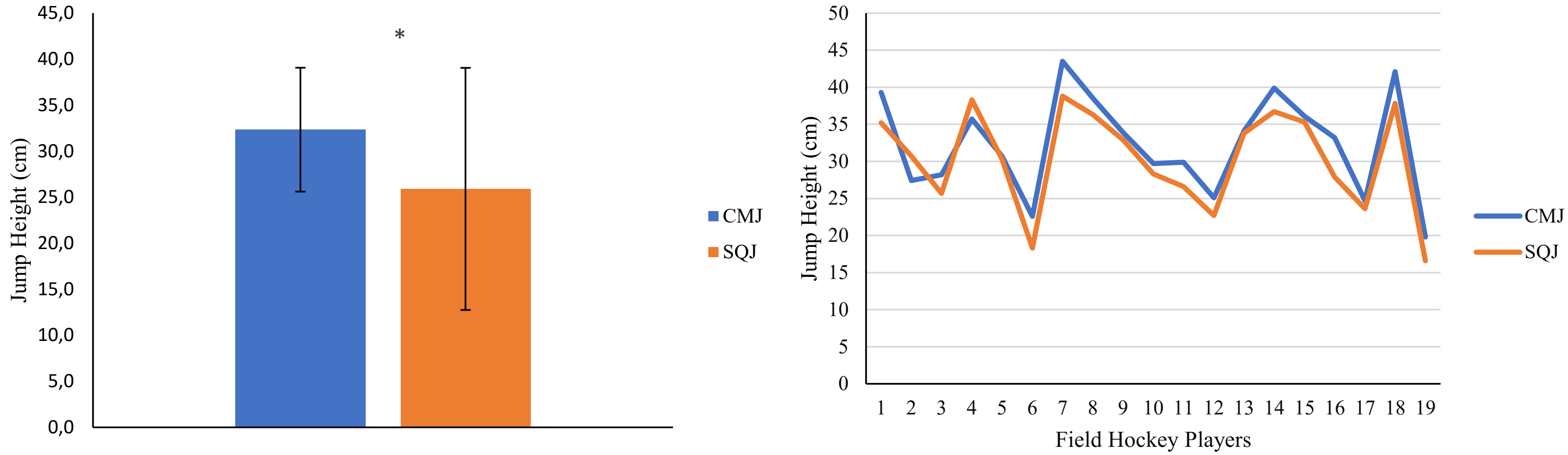


Figure 6: Jump height for countermovement jump and squat jump (p=0.001)

E. Appendix E – *Proof of journal submission*

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Title
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Authors
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Grobler, Lara
Venter, Ranel

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06-Dec-2020

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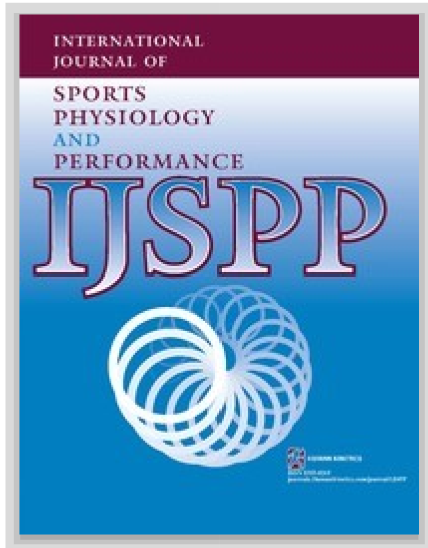

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