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The Effects of Different Post-Activation Potentiation Interventions on Speed Skating Performance

Dissertation

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I declare that I complied with this dissertation under my supervisor’s leadership and affirm that this dissertation is a representation of my work. It has not been previously included in a dissertation submitted to this institution or any other for a degree or other qualifications.

Prague, March 2025 Signature ……………………

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Abstract

This dissertation investigates strategies to enhance speed skating performance by addressing gaps in training demands, assessment methodologies, and postactivation performance enhancement (PAPE). Through three sequential studies, it explores the physiological and biomechanical demands of the sport, evaluates practical performance assessments, and examines the consistency of individualized PAPE protocols.

Given that this dissertation consists of three sequential studies, the objectives, methods, and results of the thesis are accordingly divided into three distinct sub tiers (a, b, and c), each related to an individual study. Thus, allows for a thorough and consistent understanding of the scientific methods used to answer the overarching theme of this dissertation thesis.

Title:

The Effects of Different Post-Activation Potentiation Interventions on Speed Skating Performance

Objectives:

a) Conducting a literature review to identify the current understanding on the topic and substantial gaps in the literature. Specifically, we wanted to investigate the overall development of the short-distance (500-, and 1000-meters) to middle distance (1500-meters) speed skater to provide professionals with an understanding of the demands of the sport, training methodologies, and common injuries.
b) Conduct a repeated measures study to assess the practical application of 100-meter acceleration profiling in competitive speed skaters by examining the within-session reliability and MDC of mean split times, mean velocity, and mean acceleration measures at distinct phases of 100-meter speed skating start in order to provide descriptive values of on-ice performance, with the goals of identifying performance variables for use in the development and long-term monitoring of competitive speed skaters, which can further enhance individualized training prescriptions.
c) Conduct a repeated measures study to investigate the consistency of countermovement jump height following both a high-velocity and high-force PAPE conditioning activity within individuals across multiple experimental sessions in order to determine if PAPE could be accurately predicted across multiple sessions by employing "individualized" timing.

Methods:

a) For this literature review, a search of the following electronic databases by the author AS was performed: Web of Science, CINAHL, and PubMed. Inclusion and exclusion criteria were established to account for any studies about speed skating performance between January 1960 to October 2018. Studies included the following combinations of terms: Skating, Speed skating, and Speed skate. Specific consideration was given to sprint and middle-distance speed skaters (500-, 1000- and 1500-meters).

b) Nineteen international and national elite ranked speed skaters nine male (180.5 cm ± 9.2 cm, 78.6 kg ± 10.5 kg) and ten female (168 cm ± 3.4 cm, 65.1 kg ± 4.8 kg) performed two 100-meter start trials in a single experimental session one week prior to the 2022 United States Olympic Trials. The average of two trials was used to determine 1) within-session reliability and minimal detectable change, of mean split times, velocities, and acceleration with a two-way mixed effects intra-class correlation (ICC 2,1), with coefficient of variation (CV) and the standard error of measurement (SEM) and 2) Pearson correlation coefficient (r) and coefficient of determination (R^2) were used to examine the relationship between variables derived from the 100-meter start and 100-meter final time.

c) Sixteen elite speed skaters nine males (23.1 ± 2.6 yrs., 179.1± 10.06 cm, 76.91 ± 10.72 kg, relative full back squat 1.92 ± 0.24 kg/kg) and 7 females (24.2 ± 4.7 yrs., 167.7 ± 2.55 cm, 63.58 ± 5.14 kg, relative full back squat 1.62 ± 0.23 kg/kg) of the 2021-2022 United Staes Long Track and Short Track National Teams took part in two separate and independent (yet very similar) studies consisting of six total experimental sessions 48-72 hours apart and incorporating either a potentiation protocol of five repeated band assisted countermovement jumps (BACMJ) or a potentiation protocol of a five-second maximal effort isometric squat (ISOSQ), after which, the subjects rested and performed a single maximum-effort bodyweight CMJ after 3-, 5-, and 7-minutes for each session.

Results:

a) The literature review highlights the significant coordination, strength, and power demands of sprint and middle-distance speed skaters. It provides insights for developing strength and conditioning programs tailored to athletes at various levels and identifies traits in athletes from other sports who may excel in speed skating. The review advocates strength and power training methodologies to enhance neuromuscular adaptations, which improve power production and facilitate on-ice performance. These methodologies also support broader physical development, underscoring their dual role in improving athletic performance and injury mitigation.

b) Mean split times and velocities during the 100-meter start showed strong reliability across phases (ICCs $\geq$ 0.75, CVs $\leq$ 10%). Mean acceleration exhibited moderate reliability at 20 meters but decreased at 50 meters and beyond (ICCs < 0.75, CVs > 10%). Near-perfect to perfect positive correlations were observed between split times and final 100-meter time, explaining 94%–100% of its variance, while mean velocities showed a near-perfect negative correlation, accounting for 97%–100% of the variance at 20-, 50-, and 70-meter splits. Mean acceleration at 20 meters also correlated strongly with final time (R^2 = -0.97). Minimum detectable change (MDC) values indicated high consistency for mean split times (0.10–0.15 seconds), while mean velocities exhibited greater variability, particularly at longer distances, underscoring the need for individualized interpretation of speed measures over 100 meters.

c) The results highlight inconsistencies in determining postactivation performance enhancement (PAPE). In the 1x4 ANOVA, BACMJ showed significant effects in session one, with post-jump heights at 3-, 5-, and 7-minute intervals exceeding baseline, while ISOSQ showed effects only in sessions two and four. The 1x3 ANOVA identified a significant effect for ISOSQ in session five, though post-jump heights were inconsistent. The 1x2 ANOVA consistently showed significant effects across sessions for both BACMJ and ISOSQ, with small effect sizes except for a medium effect in session two (ISOSQ at 3 minutes). Subjects did not consistently achieve peak jump heights at specific rest time, and "optimal" rest times did not significantly outperform "random" rest times. These findings suggest inconsistencies in PAPE effect on countermovement jump performance and highlight the limited repeatability of individualized PAPE responses.

Conclusion:

This dissertation advances the understanding of speed skating performance through a multidisciplinary approach. The literature review underscores the importance of strength and conditioning programs to address the biomechanical and physiological demands of the sport. Acceleration profiling provides a reliable and practical tool for assessing on-ice performance and individualizing training. However, the inconsistent PAPE effects observed across sessions highlight limitations in individualized postactivation conditioning protocols. These findings

suggest that general warm-ups may suffice for performance gains, simplifying pre-performance routines without compromising outcomes. Collectively, these studies bridge theoretical gaps and practical applications, emphasizing the need for sport-specific assessments and training strategies. They lay the foundation for future research to refine field-based methodologies and explore broader applications in speed skating and similar power-based sports.

Keywords: Speed Skating, Performance Assessment, Postactivation Performance Enhancement, Strength Training, Acceleration Profiling

Abstrakt (in the Czech language)

Tato dizertační práce zkoumá strategie pro zvýšení výkonu rychlobruslení tím, že se zabývá mezerami v požadavcích na trénink, metodologiích hodnocení a postaktivačním zvyšování výkonu (PAPE). Prostřednictvím tří po sobě jdoucích studií zkoumá fyziologické a biomechanické požadavky sportu, hodnotí praktické hodnocení výkonu a zkoumá konzistenci individualizovaných protokolů PAPE.

Vzhledem k tomu, že se tato disertační práce skládá ze tří po sobě jdoucích studií, jsou cíle, metody a výsledky práce rozděleny do tří odlišných podúrovní (a, b, a c), z nichž každá souvisí s individuální studií. Umožňuje tak důkladné a konzistentní pochopení vědeckých metod použitých k zodpovězení zastřešujícího tématu této disertační práce.

Název:

Účinky různých postaktivačních potenciačních zásahů na výkon rychlobruslení

Cíle:

a) Provedení rešerše literatury ke zjištění současného chápání tématu a podstatných mezer v literatuře. Konkrétně jsme chtěli prozkoumat celkový vývoj rychlobruslařů na krátké vzdálenosti (500 a 1 000 metrů) až střední vzdálenosti (1 500 metrů), abychom profesionálům poskytli pochopení požadavků tohoto sportu, metod tréninku a běžná zranění.

b) Proveďte studii opakovaných měření za účelem posouzení praktické aplikace profilování zrychlení na 100 metrů u závodních rychlobruslařů zkoumáním spolehlivosti a MDC středních mezičasů, střední rychlosti a středních měření zrychlení v různých fázích 100 metrů. začátek rychlobruslení s cílem poskytnout popisné hodnoty výkonu na ledě s cílem identifikovat výkonnostní proměnné pro použití při vývoji a dlouhodobém sledování závodních rychlobruslařů, kteří může dále zlepšit individuální tréninkové předpisy.

c) Proveďte studii opakovaných měření za účelem prozkoumání konzistence výšky skoku protipohybu po vysokorychlostní a vysoce silové kondiční aktivitě PAPE u jednotlivců během několika experimentálních relací, aby bylo možné určit, zda lze PAPE přesně předvídat během více relací použitím „individualizovaného “načasování.

Metody:

a) Pro tento literární přehled byl proveden průzkum v následujících elektronických databázích autora AS: Web of Science, CINAHL a PubMed. Kritéria pro zařazení a vyloučení byla stanovena tak, aby zohledňovala veškeré studie o výkonu rychlobruslení od ledna 1960 do října 2018. Studie zahrnovaly následující kombinace termínů: bruslení, rychlobruslení, rychlobruslení. Zvláštní pozornost byla věnována sprintu a rychlobruslařům na střední vzdálenosti (500-, 1000- a 1500-metrů).
b) Devatenáct mezinárodních a národních elitních rychlobruslařů devět mužů (180,5 cm ± 9,2 cm, 78,6 kg ± 10,5 kg) a deset žen (168 cm ± 3,4 cm, 65,1 kg ± 4,8 kg) provedlo dva starty na 100 metrů v jediné experimentální sezení týden před olympijskými zkouškami ve Spojených státech v roce 2022. Průměr ze dvou pokusů byl použit ke stanovení 1) spolehlivosti v rámci relace a minimální detekovatelné změny, středních mezičasů, rychlostí a zrychlení s obousměrnou korelací se smíšenými účinky v rámci třídy (ICC 2,1), s koeficientem variace (CV) a směrodatná chyba měření (SEM) a 2) Pearsonův korelační koeficient (r) a koeficient determinace (R2) byly použity ke zkoumání vztahu mezi proměnnými odvozenými z Start na 100 metrů a konečný čas na 100 metrů.
c) Šestnáct elitních rychlobruslařů devět mužů (23,1 ± 2,6 let, 179,1 ± 10,06 cm, 76,91 ± 10,72 kg, relativní dřep na zádech 1,92 ± 0,24 kg/kg) a 7 žen (24,2 ± 2,6 r. 5 cm. , 63,58 ± 5,14 kg, relativní dřep na zádech 1,62 ± 0,23 kg/kg) národní týmy United Staes Long Track a Short Track se v letech 2021–2022 zúčastnily dvou samostatných a nezávislých (přesto velmi podobných) studií sestávajících z celkem šesti experimentálních sezení 48 -72 hodin od sebe a zahrnující buď potenciační protokol pěti opakovaných pásem asistovaných protipohybových skoků (BACMJ) nebo potenciační protokol pětisekundového izometrického dřepu s maximálním úsilím (ISOSQ), po kterém subjekty odpočívaly a provedly jeden CMJ s maximálním úsilím o tělesné hmotnosti po 3, 5 a 7 minutách pro každé sezení.

Výsledky:

a) Přehled literatury zdůrazňuje významnou koordinační, silovou a silovou náročnost sprintů a rychlobruslařů na střední vzdálenosti. Poskytuje poznatky pro rozvoj silových a kondičních programů přizpůsobených sportovcům na různých úrovních a identifikuje vlastnosti sportovců z jiných sportů, kteří mohou vynikat v rychlobruslení. Přehled obhajuje metodologii silového a silového tréninku pro zlepšení neuromuskulárních adaptací, které zlepšují produkci energie a usnadňují výkon na ledě. Tyto metodiky také podporují širší fyzický rozvoj a podtrhují jejich dvojí roli při zlepšování sportovní výkonnosti a zmírňování zranění.

b) Průměrné mezičasy a rychlosti během startu na 100 metrů vykazovaly vysokou spolehlivost napříč fázemi (ICC $\geq$ 0,75, CV $\leq$ 10 %). Střední zrychlení vykazovalo střední spolehlivost na 20 metrů, ale snížilo se na 50 metrů a dále (ICC < 0,75, CV > 10 %). Mezi mezičasy a konečným časem 100 metrů byly pozorovány téměř dokonalé až dokonalé pozitivní korelace, které vysvětlovaly 94 %–100 % jeho rozptylu, zatímco střední rychlosti vykazovaly téměř dokonalou negativní korelaci, která představuje 97 %–100 % rozptylu. na mezičasech na 20, 50 a 70 metrů. Střední zrychlení na 20 metrů také silně koreluje s konečným časem (R^2 = -0,97). Hodnoty minimální detekovatelné změny (MDC) naznačovaly vysokou konzistenci pro střední mezičasy (0,10–0,15 sekundy), zatímco střední rychlosti vykazovaly větší variabilitu, zejména na delší vzdálenosti, což podtrhovalo potřebu individualizované interpretace měření rychlosti nad 100 metrů.

c) Výsledky zdůrazňují nekonzistence při určování postaktivačního zvýšení výkonu (PAPE). V 1x4 ANOVA vykazoval BACMJ významné účinky v první relaci, přičemž výšky po seskoku v 3-, 5- a 7minutových intervalech překračovaly výchozí hodnotu, zatímco ISOSQ vykazovala účinky pouze ve 2. a 4. relaci. ANOVA 1x3 identifikovala významný účinek pro ISOSQ v pátém sezení, i když výšky po seskoku byly nekonzistentní. ANOVA 1x2 konzistentně vykazovala významné účinky napříč relacemi pro BACMJ i ISOSQ, s malými velikostmi účinku s výjimkou středního účinku ve druhém sezení (ISOSQ po 3 minutách). Subjekty konzistentně nedosahovaly maximálních výšek skoku v konkrétní době odpočinku a „optimální“ doby odpočinku významně nepřevyšovaly „náhodné“ doby odpočinku. Tato zjištění naznačují nekonzistence v účinku PAPE na výkon skoku proti pohybu a zdůrazňují omezenou opakovatelnost individualizovaných reakcí PAPE.

Závěr:

Tato dizertační práce posouvá porozumění výkonu rychlobruslení prostřednictvím multidisciplinárního přístupu. Přehled literatury podtrhuje důležitost silových a kondičních programů pro řešení biomechanických a fyziologických požadavků sportu. Akcelerační profilování poskytuje spolehlivý a praktický nástroj pro hodnocení výkonu na ledě a individualizaci tréninku. Avšak nekonzistentní účinky PAPE pozorované napříč sezeními zdůrazňují omezení v individualizovaných kondicionačních protokolech. Tato zjištění naznačují, že pro zvýšení výkonu může stačit obecné zahřátí, které zjednoduší rutiny před výkonem bez kompromisů ve výsledcích. Tyto studie společně překlenují teoretické mezery a praktické aplikace a zdůrazňují potřebu hodnocení a tréninkových strategií specifických pro sport. Pokládají základ pro budoucí výzkum pro zdokonalování metodologií v terénu a prozkoumávání širších aplikací v rychlobruslení a podobných silových sportech.

Klíčová slova: Rychlobruslení, Hodnocení výkonu, Postaktivační zvyšování výkonu, Silový trénink, Profilování zrychlení

Content

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List of Abbreviations

%BF	Percent body fat
1RM	One repetitions maximum
ANOVA	Analysis of variance
AR	Active recovery
BACMJ	Band-Assisted Countermovement Jump
BW	Bodyweight
CMJ	Countermovement jump
cm	Centimeter
CI	Confidence intervals
CV	Coefficient of variation
ESD	Energy system development
GWU	General warm up
ICC	Intraclass correlation coefficient
ICRIs	Intra-complex recovery intervals
ISOSQ	Isometric squat
JH	Jump height
kg	Kilogram
kg/kg	Relative strength
m	Meter
min	Minutes
ms	Milliseconds
m/s^2	Mean acceleration
(m·s−1)	Mean velocity
MDC	Minimal detectable change
ml/kg/min	Milliliters of oxygen consumed in a minute per kilogram of body weight
mmol/L	Millimoles per liter
mm	Millimeter
MS	Maximal strength
LMM	Linear mixed effect model
LPT	Linear position transducer
P	Power

PAPE	Postactivation performance enhancement
PAP	Postactivation potentiation
r	Pearson correlation coefficient
R^2	Coefficient of determination
RFD	Rate of force development
s	Mean split time
SD	Standard deviation
SE	Strength endurance
SEM	Standard error of measurement
SMS	Submaximal strength
SP/ST	Speed-strength
ST/SP	Strength-speed
VO_2max	Maximal oxygen consumption
Vmax %	Percentage of maximum velocity at split
Wi-Fi	Wireless fidelity
W/kg	Relative power

Peer-reviewed publications included in this dissertation thesis

Chapter 3. Stuart AC, Cochrane-Snyman KC. *Strength Training and Development in Competitive Speed Skating.* Strength and Conditioning Journal, 2021. doi: 10.1519/SSC.0000000000000663 (Appendix 1)

Chapter 4. Stuart AC, Suchomel TJ, McKeever SM, Tufano JJ, Cochrane-Snyman KC. *Accelerating Performance: Reliability of Phase-Specific Measurements in Elite Speed Skaters' 100-Meter Starts.* Measurement in Physical Education and Sport, 2025. doi: 10.1080/1091367X.2025.2451615 (Appendix 1)

Chapter 5. Stuart AC, Vetrovsky T, Cochrane-Snyman KC, Vieira A, Tufano JJ. *Investigating the consistency in countermovement jump performance following high-velocity and high-force PAPE: a multi-day analysis*. Journal of Strength and Conditioning Research, 2023 (Accepted December 30th, 2024) (Appendix 1)

Peer-reviewed abstracts from conferences linked to this dissertation thesis

Suchomel TJ, McKeever SM, **Stuart AC**, Tufano JJ, Cochrane-Snyman KC. *Relationship between Countermovement Jump Force-Time Characteristics and 500-meter Sprint Time in Speed Skaters.* National Strength and Conditioning Association Annual Conference, Las Vegas, NV, USA, July 2023 (Appendix #2).

Stuart AC, McKeever SM, Tufano JJ, Suchomel TJ. *Reliability and Minimal Detectable Change of 100-meter Speed Skating Acceleration Profiling.* National Strength and Conditioning Association Annual Conference, New Orleans, LA, USA, July 2022. Journal of Strength and Conditioning Research 37(3):p e25-e272, March 2023. doi: 10.1519/JSC.0000000000004416 (Appendix #3).

McKeever SM, **Stuart AC**, Tufano JJ, Suchomel TJ. The relationships between final times and acceleration profiles within the first 100-meters of 500-meter speed skaters. J Strength Cond Res 37: e259-e260, 2022. (Appendix #4)

Tufano JJ, **Stuart AC**, Cochrane-Snyman KC, Vetrovsky T. *Reliability of Individualizing High-Force Postactivation Performance Enhancement.* National Strength and Conditioning Association Annual Conference, New Orleans, LA, USA, July 2022. Journal of Strength and Conditioning Research 37(3):p e25-e272, March 2023. doi: 10.1519/JSC.0000000000004416 (Appendix #3).

Stuart AC, Tufano JJ, Cochrane-Snyman KC, Vetrovsky T. *Reliability of Individualizing High-Velocity Postactivation Performance Enhancement.* National Strength and Conditioning Association Annual Conference, New Orleans, LA, USA, July 2022. Journal of Strength and Conditioning Research 37(3):p e25-e272, March 2023. doi: 10.1519/JSC.0000000000004416 (Appendix #3).

Stuart AC. *Assessment and Monitoring of Lower Body Strength and Power in the Elite Female Speed Skater.* Scientia Movens, Prague, Czech Republic, 2021 (Online). (Appendix #4)

Peer-reviewed Chapters from Books linked to this dissertation thesis

Stuart AC. Chapter 9 Sport Specific Speed Training – Speed Skating. In: *NSCA Developing Speed Second Edition*. Champaign, IL, USA: Human Kinetics, 2024 (Appendix #5).

1. Introduction

Long-track speed skating presents unique challenges, notably the narrow window for athletes to achieve peak performance. Typically, competitors begin as early as thirteen, with Olympic gold medalists averaging twenty-six years of age (Alles et Sport, 2014). In regions like North and South America, limited exposure to the sport exacerbates challenges in talent acquisition, development, and retention. These issues are compounded by insufficient coaching education, financial constraints, and a lack of research into the specific demands of speed skating, leaving critical gaps in effective training and assessment strategies.

Emerging research on force-velocity-power profiling shows promise for assessing on-ice performance (Perez et al., 2022; Stenoth et al., 2020; Zukowski et al., 2023). These methods support talent identification and individualized training; however, challenges persist. These include validating assessments for distances over 50 meters and integrating them with off-ice training techniques, such as postactivation performance enhancement (PAPE), enhancing power output and transfer general physical abilities to on-ice performance.

Strength training remains another underexplored area in speed skating. Between 1967 and 2015, only one comprehensive publication addressed the sport's demands (Koning et al., 2015). Despite some progress in understanding the benefits of strength and power training, such as plyometrics and sprinting (Lieberman et al., 2002; Haug et al., 2017), significant gaps remain. More research is needed to clarify how these training methods translate to enhanced on-ice performance and injury mitigation.

PAPE has emerged as a promising method for improving power output and general physical capacities. While its application in other time-trial sports has shown benefits, the literature emphasizes the need for individualized protocols to achieve sufficient results (Scott et al., 2018; Tillin & Bishop 2009). However, the consistency of PAPE effects across multiple sessions remains unclear, raising questions about its practical utility in speed skating.

Therefore, this dissertation aims to bridge these gaps by examining the demands and development of competitive speed skaters. The research focuses on identifying sport-specific demands, performance assessments, and training methodologies to enhance the general physical qualities required for on-ice success. The primary objectives are:

- To conduct a literature review identifying gaps in the understanding of speed skating's biomechanical, physiological, and energy system demands, alongside common injuries, to inform training and injury mitigation strategies.

- To evaluate 100-meter acceleration profiling for reliability and practical application, providing descriptive on-ice performance metrics for individualized training and long-term monitoring.
- To assess the consistency of PAPE effects on countermovement jump (CMJ) performance across sessions, determining whether individualized PAPE timing is viable for speed skating training.

This dissertation consists of six chapters. Chapter 1 establishes the research's rationale and overarching aims, linking identified gaps in the literature to the subsequent studies. Chapter 2 reviews current knowledge of speed skating's history, demands, and assessment methods, forming the theoretical foundation for the studies. Chapters 3, 4, and 5 detail the three studies, each published in peer-reviewed journals, addressing specific aspects of performance and training in speed skating. Chapter 6 synthesizes these findings, offering actionable insights and identifying avenues for future research.

Chapter 3 opens the original studies with the manuscript titled *"Strength Training and Development of Competitive Speed Skating,"* published June 2022 in the *Strength and Conditioning Journal* (IF = 2.490, Q3 in Sports Sciences). This manuscript presents a thorough review of the literature on the sport's needs, demands, common injuries, and physical preparation methodologies. It provides a broad understanding of speed skating's physical and tactical requirements (Stuart & Snyman, 2022). This foundational knowledge establishes the context for the subsequent studies, which investigate specific performance measures and training development.

Following this, Chapter 4 includes the manuscript *"Accelerating Performance: Reliability of Phase-Specific Measurements in Elite Speed Skaters' 100-Meter Starts,"* published January 2025 in *Measurement in Physical Education and Exercise Science* (IF = 2.2, Q2 in Sport Sciences). This study addresses the reliability and practical applications of 100-meter acceleration profiling in competitive speed skaters, providing original findings on split times, mean velocity, and acceleration across distinct 100-meter phases. The outcomes of this research lay a methodological foundation for examining speed and power measures critical to enhancing training in speed skating (Stuart et al., 2025).

Lastly, Chapter 5 presents the manuscript *"Investigating the Consistency in Countermovement Jump Performance Following High Velocity and High Force PAPE: A Multi-Day Analysis,"* accepted in December 2024 in the *Journal of Strength and Conditioning*

Research (IF = 3.2, Q3 in Sport Sciences). This study investigated whether PAPE, involving high-velocity and high-force conditioning activities, could be observed at consistent time points across multiple sessions. The findings reveal that PAPE was identifiable across sessions, but variability in countermovement jump height performance and inconsistent effects made it difficult to observe repeatable responses within individuals over time, thus questioning the idea of "individualizing" PAPE in practice (Stuart et al., 2024b).

Together, these chapters form a cohesive investigation into the multifaceted demands of competitive speed skating and propose evidence-based strategies to enhance performance.

2. Theoretical background

This chapter provides a comprehensive overview of long-track speed skating (hereafter referred to as speed skating), covering its key elements, demands, assessments, and approaches to training and physical development. By outlining these foundational aspects, the chapter sets the stage for discussing the selection, implementation, and dissemination of performance assessments that align with the sport's demands, along with strength and power training methodologies that may enhance on-ice performance

Building on this foundation, the chapter next delves into the specific needs and developmental challenges faced by competitive speed skaters, with a particular focus on countries lacking robust developmental pathways. Understanding these unique needs helps guide the choice of assessments and training methodologies, especially for short- to middle-distance skaters (500–1500 meters). This section examines the biomechanical, physiological, and energy system requirements essential for performance, providing critical context for subsequent discussions on targeted training approaches.

The chapter then shifts to a closer look at the current assessment processes for evaluating on-ice sprint skating performance, highlighting the widely used "gold standard" 30-second Wingate test on a bicycle ergometer. Beyond this traditional approach, this section explores the rationale for developing potential field-based assessments that can more directly measure how off-ice training transfers to on-ice performance. This includes assessing the practical application of postactivation performance enhancement (PAPE) as a method to maximize training adaptations, reinforcing the need for assessments that reflect real-world performance demands.

Moving into the training methodologies themselves, the chapter introduces PAPE as a strategy for translating general physical development from off-ice training to on-ice performance. Referencing findings from Chapter 3 (Stuart & Snyman, 2022), this section emphasizes that neuromuscular adaptations from resistance training can yield substantial benefits for competitive speed skaters. As such, PAPE is proposed as a promising approach to enhance the physical qualities required for on-ice performance, offering a bridge between off-ice strength training and development and on-ice application.

In conclusion, this chapter aims to provide a comprehensive understanding of the unique demands, assessments, and training methodologies for competitive speed skaters. By addressing these elements, the chapter lays theoretical groundwork for identifying training prescriptions and monitoring protocols that may contribute to performance improvements in speed skating.

2.1. Essential Aspects of Speed Skating

This section provides a brief overview of foundational topics also covered in Chapter 3 (Stuart & Snyman, 2022), where a more detailed discussion can be found. Speed skating, a sport with a rich history dating back to the 13th century in the Netherlands, evolved from a mode of transportation to organized competitions. It debuted in the Olympic Winter Games in Chamonix in 1924 (Houdijk et al., 2003). Official competitions typically begin at age thirteen, yet Olympic gold medalists average twenty-six years of age, reflecting the sport's demanding developmental trajectory (Alles Met Sport, 2014).

The primary objective in speed skating is to maintain maximal power output throughout the race, aligning its physiological demands with those of high-power sports like track and field, track cycling, and swimming (de Koning, 2011). Sprint events (500m and 1000m) demand anaerobic power, with international times ranging from 33.6 to 71.6 seconds. The 1500m event requires a balance between anaerobic and aerobic energy systems, with times between 1 minute 40 seconds and 1 minute 49 seconds (Stuart & Snyman, 2022).

Advancements in technology, including klapskates, aerodynamic suits, high-altitude training, and refined ice preparation, have contributed to improved performance times (de Koning, 2010). However, these advancements do not eliminate existing challenges. Limited resources and logistical constraints in countries like North and South America hinder talent identification and development. This disparity underscores the importance of understanding speed skating's unique physiological and biomechanical demands to address training gaps.

Speed skating's biomechanics, particularly the deep crouched position required to reduce drag and sustain aerodynamic efficiency, place significant demands on the lower body. Athletes must develop strength, joint stability, and mobility to maintain this posture while producing maximal lateral force during push-off. The ability to minimize drag is critical to efficient power transfer. These biomechanical characteristics influence training strategies, necessitating exercises such as strength training and plyometric drills to develop lateral force production.

Energy system development (ESD) also plays a pivotal role. Short-distance events rely heavily on anaerobic glycolysis, while middle-distance races demand a balance between anaerobic and aerobic systems. Tailored ESD programs, designed to improve both explosive power and sustained speed, are vital for on-ice performance. Despite progress, gaps remain in transitioning ESD-focused off-ice training to measurable on-ice improvements.

By integrating insights into speed skating's historical context and its unique physiological and biomechanical demands, coaches and performance staff can create assessments and training programs tailored to the sport's requirements. These programs can help athletes overcome challenges, maximize performance, and foster long-term development in competitive settings.

2.2. Physiological Demands

Building on the physical requirements outlined, this section examines physiological mechanisms integral to speed skating performance, where athletes rely on both aerobic and anaerobic energy systems to sustain the high-power outputs critical for success (Stuart & Snyman, 2022). The balance between these systems varies by event distance. Sprint races (500 and 1000 meters) predominantly utilize anaerobic energy (30–70%), while the 1500-meter event draws on aerobic sources for 30–51% of total energy expenditure (de Koning et al., 2005; Foster et al., 2003; Haug et al., 2017).

In sprint events, biomechanical factors like small knee and hip angles, combined with a low, static body position, contribute to extended ground contact times that intermittently restrict blood flow (Orie et al., 2014). This occlusion effect shifts the energy demand toward the anaerobic system, as reflected in elevated blood lactate concentrations and reduced muscle oxygen saturation during performance (Rundell et al., 1997; Hesford et al., 2013). Studies have shown blood lactate levels exceeding 15 mmol/L in elite speed skaters, underscoring the extreme reliance on anaerobic glycolysis in these events (Yu et al., 2012). Speed skating's unique physiological demand is further highlighted by the requirement to exceed the maximal lactate steady state, a characteristic that sets it apart from other endurance sports (Foster et al., 1999; Orie et al., 2014).

The 1500-meter event requires a more balanced approach, with significant contributions from both aerobic and anaerobic systems. Research indicates that athletes achieving optimal times in this event display a high aerobic capacity (VO_2max values > 65 $mL \cdot kg^{-1} \cdot min^{-1}$) coupled with strong anaerobic power outputs (Haug et al., 2017). Aerobic conditioning supports recovery between high-intensity efforts and maintains energy output over the longer race duration, emphasizing the importance of integrating aerobic endurance training into speed skating programs (Foster et al., 2003; Yu et al., 2012).

Speed skating's unique posture, particularly the deep crouched position required for aerodynamic efficiency, creates additional physiological challenges. The sustained small knee and hip angles increase muscle activation in the quadriceps and gluteal muscles, intensifying fatigue and contributing to early onset muscular exhaustion (Orie et al., 2014). Furthermore, the occlusion effect limits oxygen delivery to working muscles, requiring athletes to develop exceptional fatigue resistance and anaerobic capacity to sustain performance under hypoxic conditions (Hesford et al., 2013).

Given these physiological demands, speed skating training incorporates a high proportion of moderate- to high-intensity work (Zones 2 and 3) (Orie et al., 2014). For sprint and middle distances (500, 1000, and 1500 meters), such training supports performance while maintaining a balance between intensity and volume. However, excessive anaerobic training can impair endurance performance in longer distances (3000 meters and beyond), necessitating a nuanced approach to training periodization (Haug et al., 2017). Tailored programs that emphasize event-specific ESD are essential, optimizing the balance between anaerobic and aerobic conditioning to meet the diverse demands of each race distance.

2.3. Biomechanical Demands

Speed skating shares biomechanical similarities with other sports performed in similar environments, such as ice hockey, and time-trial activities like track cycling and sprinting. However, speed skating's unique biomechanical requirements distinguish it from these activities, particularly in the way athletes generate and sustain high horizontal velocities while minimizing ice friction (de Koning et al., 2000; Edwards et al., 2021; Konings et al., 2014).

In sprint events (500m and 1000m), performance centers on an explosive start and rapid acceleration. Skaters rely heavily on the push-off phase to generate forward momentum, engaging the gluteus maximus, vastus medialis, and other extensor musculature to produce the substantial force needed during the initial strides (de Boer et al., 1987). This phase is marked by short ground contact times and high knee extension velocities, which amplify force application onto the ice (Buckeridge et al., 2015; Robbins et al., 2018). The ability to rapidly apply force in this phase is critical, as it allows skaters to transition from a static two-point or three-point position to peak acceleration in under 20 meters (de Koning et al., 1995; Houdijk et al., 2003; Stuart, 2025).

Biomechanical adaptations during this phase are particularly influential in sprint distances, where anaerobic energy systems dominate. Short, explosive movements and a compact crouched position reduce drag and maximize power transfer. Additionally, the mechanical power outputs required to reach top speeds during the first 70 meters are among the highest across all race distances (de Koning et al., 2000). These demands necessitate targeted strength training, focusing on force production, plyometric drills, and explosive power exercises to optimize acceleration and maximal velocity phases (Stuart & Snyman, 2022).

As skaters progress beyond the initial 20 meters, they transition from a "running-like" technique to a more efficient "gliding" motion. This shift, characterized by increased knee extension velocity and longer push-off times, is essential for maintaining top speed while minimizing energy expenditure (de Koning et al., 2000; Stuart & Snyman, 2022). The glide phase consists of three distinct components—glide, push-off, and reposition—which collectively enhance mechanical efficiency and allow skaters to sustain speeds through the straightaway and corner transitions (Stuart & Snyman, 2022; Zukowski et al., 2023).

Biomechanical demands differ significantly between sprint and middle-distance races (1500m). While sprint events prioritize peak power output, middle-distance events require a balance between power and efficiency to conserve energy for the latter stages of the race. Skaters in middle-distance events must maintain a deep crouched posture (~15° torso angle) over a prolonged period of time, increasing demands on quadriceps and gluteal endurance (de Boer et al., 1987; Stefani, 2006; Stuart & Snyman, 2022). This endurance component is critical for maintaining consistent push-off forces, particularly during repeated transitions from straightaways to corners.

The corners pose distinct biomechanical challenges due to centrifugal forces encountered at high speeds. To counteract these forces, skaters adopt a leftward lean, requiring precise control of body position and weight distribution (Zukowski et al., 2023; de Koning et al., 1991). Studies have shown that during cornering, the left leg generates higher peak power and experiences shorter ground contact times compared to the right leg, reflecting its primary role in counteracting lateral forces (Zukowski et al., 2023). These asymmetrical demands highlight the importance of bilateral strength training and exercises targeting lateral stability and control.

Skaters' ability to maintain power output through the glide, push-off, and reposition phases during cornering directly impacts their performance, particularly in longer events where repeated cornering cycles exacerbate fatigue (Allinger et al., 1997; de Boer et al., 1987; Stuart & Snyman, 2022). Developing core strength and lower-body endurance is critical to addressing these biomechanical challenges and ensuring efficient cornering mechanics throughout the race.

The biomechanical differences between sprint and middle-distance events necessitate tailored training strategies. Sprint-focused skaters benefit from high-intensity anaerobic training, emphasizing explosive strength, acceleration, and maximal velocity development. In contrast, middle-distance skaters require a hybrid approach that balances anaerobic power with aerobic endurance to sustain efficiency over longer race durations. Biomechanical analysis and targeted conditioning, such as strength exercises to manage fatigue during cornering, are essential for optimizing performance across distances (Houdijk et al., 2003; Stuart & Snyman, 2022).

By delving into the specific biomechanical demands of speed skating, this section underscores how tailored training methodologies can enhance performance across race distances. These insights provide a foundation for understanding the interplay between biomechanics and race-specific strategies, emphasizing the critical role of individualized conditioning programs.

2.4. Assessments in Speed Skating

A well-designed performance assessment should demonstrate strong predictive validity, reflecting the relationship between test results and competitive skills or specific exercises (Zukowski et al., 2023). As highlighted in Chapter 3 (Stuart & Snyman, 2022), traditional laboratory-based assessments have provided valuable insights into the physiological qualities critical for on-ice success (Table 1). Common tests include VO_2max assessments using a graded refusal protocol on a stationary bicycle ergometer (Lukanova-Jakubowska et al., 2021), 6-second and 30-second Wingate tests, and lactate profiling to evaluate both aerobic and anaerobic capacities (Geijsel et al., 1984; Hofman et al., 2017).

Table 1. Sample Speed Skating Testing Battery

Assessment	Test	Procedure	Order	Frequency	Range of Performance
Anthropometric	Sum of 7 Skinfold Measurement	Santos et al. 2014 (36)	1st	6-8 weeks	Females 30-50mm Males 50-90mm (36)
Lower Body Power	Countermovement Jump Height	Runner et al. 2015 (35)	2nd	4-12 weeks	.49m - .60m
Lower Body Strength	1RM Back Squat	Runner et al. 2015 (35)	3rd	8-12 weeks	1.5-2.1 kg/kg
Anaerobic Power	Wingate 6s Peak Power Test	Hoffman et al. 2017 (23)	4th	8-12 weeks	Males 16-21 w/kg Females 13-17 w/kg (23)
Anaerobic Capacity	Wingate 30s Anaerobic Capacity	Hoffman et al. 2017 (23)	5th	6-8 weeks	Males 9-11 w/kg Females 7-9 w/kg (23)
Aerobic Capacity	Beep Test	Delisle-Houde et al. 2018	6th	8-12 weeks	Males VO2max: 57.2-62 ml/kg/min Females VO2max: 52.2-54.9 ml/kg/min (7,9,38)

Among these, the Wingate test has been particularly influential in evaluating lower-body power outputs in speed skaters, correlating with sprint and endurance performances over 500 and 1500 meters (Smith & Roberts, 1991; Foster et al., 1993; Greeff et al., 2011). However, despite its historical utility, the Wingate protocol has notable limitations. Research indicates that it lacks sensitivity in tracking training adaptations over time, especially within homogeneous groups of elite athletes (van Ingen Schenau et al., 1992; Foster et al., 1993). This limitation is compounded by its dependence on off-ice conditions, which may not fully replicate the biomechanical and neuromuscular demands of on-ice skating.

Additionally, the infrequency of laboratory assessments, typically conducted only during early and late preparatory phases (April–September), creates challenges for monitoring physiological adaptations throughout the competitive season. Seasonal variations in body mass, training focus, and external conditions further reduce the relevance of these tests in tracking longitudinal performance changes (Hoffman et al., 2017). As a result, while laboratory tests like Wingate remain useful for baseline profiling, they may not offer the specificity required to link training adaptations directly to on-ice improvements.

To address these gaps, recent research has emphasized the development of field-based assessments to better reflect the mechanical and physiological demands of on-ice performance. These assessments, utilizing technologies like photoelectric cells, radar systems, and horizontal robotic resistance devices, enable coaches to evaluate acceleration and sprint profiles in more realistic contexts. Split time analysis, for example, has demonstrated strong reliability in assessing mechanical factors influencing skating performance during initial acceleration (0–10 meters) and top speed phases (0–30 meters) (Laakso & Secomb, 2023; Lafontaine, 2007; Stenroth et al., 2020; Zukowski et al., 2023). Exponential modeling of these phases has yielded excellent intraday consistency, offering a promising alternative to traditional laboratory tests (Zukowski et al., 2023).

Despite these advances, field-based assessments face limitations that must be addressed for widespread implementation. One significant concern is their current focus on shorter distances (e.g., 50 meters), which do not fully encompass the demands of competitive events such as the 100-meter sprint. Expanding the assessment range to include longer distances could improve the predictive validity of these tests and provide a more comprehensive evaluation of performance across acceleration phases. Another consideration is the practicality of these assessments for coaches. While technologies like radar and robotic resistance devices are promising, their accessibility and cost may limit their adoption in resource-constrained environments. Simplified and cost-effective alternatives, such as photoelectric cell timing systems, could enhance feasibility without sacrificing reliability.

Integrating force-power-velocity (acceleration) profiling into these assessments offers additional benefits. This approach allows practitioners to identify key performance measures, such as peak power output and optimal acceleration strategies, tailored to individual skaters. Such profiling could also improve talent identification processes, ensuring athletes with specific physiological and mechanical characteristics are identified and developed early in their careers. To advance the utility of these assessments, future research should focus on a.) extending the range of field-based tests to cover competitive distances (e.g., 100 meters or longer), b.) exploring cost-effective and portable technologies for broader accessibility, c.) validating these assessments in diverse populations and training environments to ensure generalizability.

In conclusion, while traditional assessments like Wingate tests have been foundational in speed skating, their limitations highlight the need for more specific, practical, and adaptable methods. Field-based assessments, when refined and implemented effectively, could significantly enhance performance monitoring and athlete development, offering coaches actionable insights into the longitudinal progress of their skaters.

2.5. Training and Development

Over the past three decades, training methodologies for elite speed skaters have evolved significantly, with a strong focus on integrating strength training and intensity distribution models within an annual periodization framework. Polarized training models, which strategically balance high-intensity and low-intensity workloads, have become central to athlete development, enabling skaters to optimize both power and endurance (Orie et al., 2014).

2.5.1. Strength and Conditioning Considerations

Strength and conditioning programs play a critical role in addressing speed skating's unique demands, where high force production and explosive power are essential for overcoming ice friction and maintaining horizontal velocity. Neuromuscular adaptations—particularly improvements in strength, power, and the rate of force development (RFD) are central to enhancing performance (Hedrick, 1994; McCarthy, 2003). RFD development enables skaters to generate peak forces rapidly, aligning with the biomechanical demands of short ground contact times during the push-off phase (Suchomel et al., 2016).

Maximal and explosive strength training, including Olympic weightlifting derivatives and plyometrics, has shown strong transferability to on-ice performance. Studies from comparable sports, such as track cycling and ice hockey, demonstrate that such training reduces oxygen consumption and increases time to exhaustion at maximal aerobic power, suggesting similar benefits for speed skating (Silva et al., 2014; Del Vecchio et al., 2019; Laakso & Schuster, 2021). Sprint training has also been linked to improved starts in short-track speed skating, highlighting the importance of integrating sprint mechanics with on-ice performance goals (Haug et al., 2017).

Periodization strategies for strength training must balance off-ice strength development with the technical demands of on-ice performance. For example, during the general preparatory phase (April–September), when ice access is limited, strength and off-ice simulation exercises (e.g., inline skating) dominate the training schedule. As the competitive season approaches, the emphasis shifts toward refining on-ice skills and maintaining strength without detracting from technical proficiency (Orie et al., 2014; Stuart & Snyman, 2022) (Table 2). This dynamic balance underscores the importance of periodized strength training that aligns with the athlete's competition schedule and race-specific demands.

Table 2. Theoretical Annual Macrocycle for Speed Skating

Month	**April**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
Seasonal Phase	General Preparatory				Specific Preparatory		Pre-Competition		Competition			Transition
Training Phase	Strength Endurance, Submaximal Strength, and Power Development				Maximal Strength, Strength-Speed		Strength-Speed, Maximal Strength		Speed-Strength, Strength-Speed, Submaximal Strength			Active Recovery
Training Focus	SE	SMS	MS	P	MS	ST/SP	ST/SP	ST/SP	SP/ST	SP/ST	SP/ST	AR
Duration (Weeks on/Weeks off)	2-3/1	2-4/1	2-4/1	2-3/1	2-4/1	2-3/1	2-3/1	2-3/1	-	-	-	2-3/1

Notes:
SE = Strength Endurance, SMS = Submaximal Strength, MS = Maximal Strength, P = Power, ST/SP = Strength-Speed, SP/ST = Speed-Strength, AR = Active Recovery

2.5.2. Post Activation Potentiation (PAP) and Post Activation Performance Enhancement (PAPE).

PAPE has emerged as a valuable training methodology for speed skating, where explosive lower-body strength is a key performance determinant. The physiological mechanisms underlying PAPE include increased motor unit recruitment, phosphorylation of myosin regulatory light chains, and temporary alterations in muscle pennation angle (Bazevich & Babault, 2019; Boullosa et al., 2018; Docherty & Hodgson 2007; Tillin & Bishop, 2009; Rassier & Macintosh 2000,). These mechanisms collectively enhance the force and power output of subsequent efforts, making PAPE particularly relevant for explosive sports like speed skating (Prieske et al., 2020; Stuart & Snyman, 2022.).

In practice, PAPE is typically achieved through potentiating complexes, which pair a high-intensity conditioning activity (e.g., heavy squats or isometric holds) with a biomechanically similar plyometric exercise (e.g., vertical jumps) (Lee et al., 2014). For speed skating, unilateral conditioning activities, such as single-leg isometric squats, have demonstrated potential for enhancing mean power output in elite athletes (Gimenez et al., 2018). These findings suggest that carefully timed conditioning activities can enhance explosive skating efforts, especially in sprint distances like the 500m and 1000m.

While PAPE offers promising benefits, limitations must be acknowledged. For example, the effects of PAPE are highly variable and have been said to be influenced by factors such as training age, conditioning activity intensity, and rest intervals (Dolan et al., 2017; Fukutani et al., 2014; Kartages et al., 2019; Kilgallon & Beard 2010; Mina et al., 2016; Chiu et al., 2003; Chiu et al., 2012; Cazas et al., 2013; Prieske et al., 2020). Many studies, including those on speed skating, have small sample sizes and limited session designs, making it difficult to generalize findings or improve protocols (Gimenez et al., 2018). Additionally, the repeatability of PAPE effects across multiple sessions remains unclear, leaving questions about its long-term application in speed skating programs.

Despite these challenges, PAPE remains a valuable tool when incorporated thoughtfully into periodized training plans. Future research should explore the impact of individualized rest intervals, long-term adaptations, and event-specific applications of PAPE in speed skating. Addressing these gaps will allow coaches to better predict and enhance outcomes for high-intensity events such as the 500m, 1000m, and 1500m distances.

In conclusion, the integration of strength training, periodized programming, and PAPE offers a multifaceted approach to addressing the unique demands of speed skating. By aligning training methodologies with race-specific requirements, athletes can enhance power, endurance, and technical proficiency for peak performance.

3. Strength Training and Development in Competitive Speed Skating

To date, the sport of Speed Skating has seen limited exposure in Western countries, such as the United States. Consequently, the training, development, talent identification, and talent retention in this sport can be particularly challenging. This manuscript serves as a valuable resource, offering crucial insights to coaches, athletes, and strength and conditioning professionals. It focuses on the biomechanical, physiological, and energy system demands of speed skating, providing the groundwork for developing comprehensive strength and conditioning programs, catering to athletes at all levels, from the elite to club skaters. The findings presented in this manuscript suggest that elite-level speed skaters share similar physiological profiles with their Olympic counterparts in time trial sports, such as track and field, track cycling, and swimming. Moreover, they exhibit similarities with athletes in environmental sports like ice hockey.

A most recent comprehensive review on the topic of speed skating (Konings et al 2015) provides an overview of the sport's needs and demands. However, it didn't provide much or anything about the necessary general physical abilities nor the development of these qualities on-ice or off-ice through strength and conditioning training. Additionally, specific publications have addressed this lack of knowledge through practical application manuscripts (Hedrick 1994; McCarthy 2003). However, the relevance of these two publications may be lessened due to the large gap in time since originally published and the advancement in the field of strength and conditioning.

Therefore, the first manuscript of this dissertation thesis titled "*Strength Training and Development in Competitive Speed Skating"* (Stuart & Snyman, 2022) sought to provide an updated and comprehensive review on the biomechanical, physiological, energy system demands of speed skating, providing the groundwork for developing comprehensive strength and conditioning programs, thereby providing the foundation for further research within the subject population.

The resulting manuscript was published in 2022 in the Strength & Conditioning Journal.

Strength Training and Development in Competitive Speed Skating

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Abstract:

Speed skating is a time trial-based sport which requires skill, strength, power, and capacity. The unique demands of the sport require a thorough need analysis to better understand the physical requirements, potential injuries, and periodization to successfully prepare athletes. This article will focus on the overall development of the short to middle-distance speed skater, to provide coaches, athletes, and strength and conditioning professionals an understanding of the biomechanical, physiological, and energy system demands of the sport and to identify common injuries that are sustained from repeated efforts.

Keywords: Speed Skating, Periodization, Injury Prevention, Strength, Power, Energy System Development

Key Takeaways:

- There is a limited amount of literature on strength training and the development of the competitive speed skater.
- Speed skating athletes require high levels of coordination, strength, and power similar to their peers in other Olympic time-trial based sports.
- Neuromuscular adaptations related to strength and power training have been shown to reduce overall time trial performance.
- This publication demonstrates the need to develop strength and power in the competitive speed skater and that both plyometric and sprint training have been found to correlate to aspects of on-ice speed skating performance.

3.1. Approach to Identifying the Problem

3.1.1. History of Speed Skating

Speed skating, a sport with origins in the 13th century Netherlands, made its Olympic debut at the 1924 Chamonix Winter Games (Houdijk et al., 2003). It encompasses various disciplines, including long track, short track, and marathon. This manuscript focuses on long-track speed skating, particularly the short-distance (500 and 1,000 meter) and middle-distance (1,500 meter) events. Unlike other sports, long-track speed skating is a time trial competition where athletes race against the clock, although they do so in pairs, introducing an element of head-to-head competition. Events are classified into sprints (500 and 1,000 meter), middle distances (1,500 meter), and long distances (3,000, 5,000, and 10,000 meter) (Houdijk et al., 2003). The World Cup circuit, held annually in North America, Asia, and Europe, spans the fall and winter, culminating in early March. These competitions are crucial as skaters compete for World Cup points and medals as well as Olympic quota spots.

3.1.2. Similarities to other sports

Despite being a distinct discipline, short-track speed skating shares distances, biomechanical and physiological traits, and training regimens with long-track skating. Similarities also exist with other sports, such as ice hockey, in terms of biomechanics, energy system demands, and potential injuries. In 2014, Konings et al. (Konings et al., 2014) conducted a comprehensive review of the literature on speed skating from 1971 to 2014, examining various factors, including anthropometric, technical, physiological, tactical, and psychological characteristics of skaters. The review highlighted key insights, such as the significance of small knee and trunk angles among elite skaters, the ongoing pursuit of optimal pacing strategies, the performance benefit of losing 1 kilogram of body fat, and the need for more research on psychological practices like self-regulation. Hofman et al. (Hofman et al., 2017) supported these findings, noting that Wingate testing is a strong predictor of 1,500-meter performance. However, research specifically focused on strength and power training in speed skating remains limited.

3.1.3. Primary aim of manuscript

With the scarcity of literature and the sport's limited exposure in Western countries, especially the United States, present challenges for training and coaching speed skaters. This lack of visibility can impede the transition of athletes from related sports. This manuscript aimed to explore the development of short distance to middle-distance speed skaters, providing valuable insights for coaches, athletes, and strength and conditioning professionals regarding the biomechanical, physiological, and energy system demands of the sport, as well as common injuries.

3.1.3.a. Inclusion/Exclusion criteria

Inclusion and exclusion criteria were established to account for any studies about speed skating performance between January 1960 to October 2018. Studies included the following combinations of terms: Skating, Speed skating, Speed skate. Specific consideration was given to sprint and middle-distance speed skaters (500-, 1000- and 1500-meters). Initial results identified 790 peer-reviewed publications based on research from PubMed, CINAHL, and Web of Science. After exclusion and full text review only 49 articles ended up meeting the inclusion criteria.

3.2. New Additions to Literature

The first manuscript of this thesis (Stuart & Snyman, 2022) addresses the limited existing literature on speed skating by providing a comprehensive needs analysis of the sport. According to the analysis, the primary objective for speed skaters is to sustain high-power output throughout the race, necessitating adaptations in technique, bioenergetic demands, strength, and power across different event stages.

3.2.1. Movement Analysis

The race begins with a powerful, anaerobic start, similar to track events, followed by a transition to a gliding phase with quicker knee extensions and a more horizontal torso position to optimize for turns (de Koning & Van Ingen Schenau 2000; 24; 25; Stuart & Snyman 2022). Skaters then cycle through glide, push-off, and reposition phases, using sideward pushes for propulsion while maintaining a low, horizontal torso to minimize air resistance (Allinger et al., 1997; de Boer et al., 1987; de Koning et al., 2005; Stefani et al., 2006) (Figure 1).

Figure 1. Sideward push

Once past the initial start and first corner, the skater's movements adopt a wave-like pattern, cycling through glide, push-off, and reposition phases (Allinger et al., 1997; de Boer et al., 1987; de Koning et al., 2005; Houdijk et al., 2003) (Figure 2). During the glide phase, the skater cannot push backward effectively; propulsion is achieved by a sideward push at a right angle to the glide, maintaining speed with a low, horizontal torso position to reduce air resistance (Allinger et al., 1997; de Boer et al., 1987; de Koning et al., 2005; Stefani et al., 2006). The push-off is mainly driven by knee and hip extension, though full extension is not reached before moving into the next stroke (de Koning & Van Ingen Schenau 2000; Muehlbauer et al., 2010).

Figure 2. Transition to reposition

3.2.2. Pacing Strategies

Both aerobic and anaerobic energy systems are crucial in speed skating, with their contributions varying by event distance (Foster et al., 1994; Foster et al., 2003). For shorter events like the 500-meter and 1000-meter, anaerobic energy predominates, while longer distances like the 1500 meter require a balanced use of energy systems, including a significant aerobic component (de Koning 2000; de Koning et al., 2005; de Koning et al., 1992; Deweese et al., 2015; Miehlbauer et al., 2010a; Miehlbauer et al., 2010b; Van Ingen Schenau et al., 1990). Effective race strategies often involve rapid initial acceleration followed by controlled deceleration to manage energy reserves efficiently (Foster et al., 1994; Foster et al., 2003).

3.2.3. Potential Musculoskeletal Injuries

Injuries in speed skating, though not extensively studied, commonly affect the knees, ankles, spine, legs, and groin, with both on-ice and off-ice training contributing to injury rates (Quinn et al., 2001). Similarities with sports like ice hockey suggest common biomechanical and training demands (Nightingale 2014). Injury prevention strategies include proper warm-up routines, adequate preparatory training, core strength development, and careful management of training loads (Table 3) (Stuart & Snyman 2022).

Table 3. Loading sources, risk factors, and practical considerations in speed skating

Training volume sources	Potential injuries	Considerations
Static dryland	Patellofemoral injuries and low back pain	Ensure proper dynamic warm-up protocols including dynamic stretching and core activation
Bike/Training Camp	Low back pain and knee irritation	Adequate accumulation of preparatory volume before camp. Adequate development of core and hip/knee extensor musculature.
Increase lap volume	Low back pain	Adequate accumulation of preparatory volume before camp. Adequate development of core and hip/knee extensor musculature.
Intensive plyometric session	Patellofemoral injuries and low back pain	Adequate development of core and hip/knee extensor musculature. Ensure proper warm-up protocol including dynamic stretching and core activation. Ensure athletes are implementing self-myofascial release strategies such as foam rolling into their cool-down and warm-up procedures.

3.2.4. Anthropometrics and Performance

Anthropometric data indicate that elite speed skaters typically have average height and mass but possess shorter legs, longer trunks, and well-developed thigh musculature, emphasizing the importance of lower body strength (Sovak & Hawes 1987). Additionally, lower body fat percentages, particularly in female athletes, can provide a competitive edge (Akahane et al., 2006; Sovak & Hawes 1987).

3.2.5. Strength and Conditioning Considerations

3.2.5.a. Neuromuscular Adaptations

Neuromuscular adaptations, such as increased strength and power, are vital for enhancing on-ice performance. Training programs focusing on strength and power, including plyometrics and sprinting, improve force production and reduce oxygen cost, leading to increased skating speed and efficiency (Coetzee & Malan 2018; Del Vecchio 2019; Patono & Hopkins 2005; Silva et al., 2014; Stefani 2006; Sunde et al., 2010; Van Ingen Schenau 1990).

3.2.5.b. Metabolic Adaptations

Conditioning for speed skaters requires a mix of high-intensity, short-duration training and low-intensity, long-duration work. A periodized training approach (Table 4), beginning with aerobic base building in the off-season and progressing to more specific conditioning like lactate threshold training, prepares athletes for the sport's diverse demands (Stuart & Snyman 2022).

Table 4. Theoretical metabolic annual training program for the speed skating athlete

Seasonal Period	Transition Period	General Physical Period	Specific Preparatory Period	Competition Period
Goals	Improve Aerobic Capacity	Aerobic Power, Anaerobic Threshold	Conversion	Specific Endurance, Aerobic Capacity
Specific Training	Tempo Running, Cardiac Output	Threshold Training, Alactic Power, Alactic Capacity	Lactate Power and Lactate Capacity	Complete sprints, Competitions Competition simulations, Tempo
Examples	Circuit Training, Tempo Runs	Hill Sprints, Resisted Sprinting, Fartlek	Interval Training, Sport-Specific Endurance, Speed-Endurance	Time trials, various competitive and noncompetitive distances at race pace

3.2.5.c. Periodization

Periodization is crucial in designing effective training for speed skaters, as it provides a structured framework to develop specific fitness characteristics (Hedrick 1994; McCarthy 2003). A sequential periodization approach is most effective for speed skaters as it enables phase potentiation, enhancing power through muscle cross-sectional area (mCSA), force production, and nervous system adaptations (Deweese et al., 2015a; Deweese et al., 2015b; Deweese et al., 2016).

a. **General Preparatory Phase:** Focuses on strength endurance, hypertrophy, and anaerobic energy production through higher training volumes at low to moderate intensity (60-80% 1RM). This phase lays the groundwork for handling intensive on-ice and off-ice training (Table 5).

Table 5. Example of general preparatory period - Strength-endurance mesocycle

Order	Exercise	Sets	Reps/Duration	%1RM	Rest
Technique/Skill	Slide board	1-2	5-6 at 7-10s	N/A	2-5 min
1	Back squats	3-5	8-10	50-85%	2-5 min
2	Clean pull to knee or from floor	5-6	5	70-85%	2-5 min
3	Push press	3	8-10	50-85%	2-5 min
4	Barbell step up	3	8-10	50-85%	2-5 min
5	Core Stability	3	10	N/A	30-90s

The session is aimed at improving the athlete's physiological adaptations to perform high-intensity strength and power training. Technique/skill work is separated from lifting sessions by a minimum of 3-4 hours to ensure proper recovery

b. **Specific Preparatory Phase:** Advances training to develop maximal strength by increasing intensity with a reduction in volume (reps x sets). This improves force production and rate of force development (RFD), critical for accelerating on-ice (Table 6).

Table 6. Example of specific preparatory period – Maximal Strength mesocycle

Order	Exercise	Sets	Reps/Duration	%1RM	Rest
Technique/Skill	On-ice skating	2-4	3 x 90-120s	N/A	2-3 min
1	Power clean	3-5	1-2	80-90%	2-5 min
2	Back squats	3-5	2-3	75-90%	2-5 min
3	Pulls from floor	3-5	2-3	>100%	2-5 min
4	Jump Squats	3	5	BW-30%	2-5 min
5	Barbell Split Squats	3-5	5	75-85%	2-5 min
6	Core Stability	3	10	N/A	30-90s

The session is aimed at developing strength and greater loads as well as moving relatively high loads quickly. Technique/skill work is separated from lifting sessions by a minimum of 3-4 hours to ensure proper recovery.

c. **Competition Phase:** Shifts emphasis to strength-speed and speed-strength through power and ballistic training. Postactivation Performance Enhancement (PAPE) complexes maintain maximal strength and explosiveness while reducing volume (reps x sets) to prioritize preparedness and minimize interference with on-ice performance. (Table 7).

Table 7. Example of competition period - Speed-strength (PAPE)

Order	Exercise	Sets	Reps/Duration	%1RM	Rest
Technique/Skill	On-ice skating	3-4	Race Distance	N/A	
1	Countermovement Jumps	3-5	3	30-50%	5-10 min
2a	Rear Foot-Elevated Split Squats	3-5	2-3	80-85%	2-5 min
2b	Skate-specific Jumps	3-5	5	BW	2-5 min
3	Single Leg DB RDL	3	5	N/A	2-5 min
4	Core Stability	3	10		30-90s

The session is aimed at improving speed-strength through the utilization of ballistic movements and potentiation complexes.

Throughout the annual training plan, coaches must account for external stressors from cross-training activities (e.g., cycling, inline skating, running, etc.) to avoid overtraining. Regular communication between strength and conditioning professionals, sport coaches, and performance staff is essential to ensure training interventions align with the athlete's competitive schedule and recovery needs (Stuart & Snyman, 2022).

3.3. Conclusion

The findings from the first manuscript of this thesis (Stuart & Snyman, 2022) provide a detailed analysis of the physical and physiological demands of speed skating. The sport necessitates sustaining high-power output and adapting to varying bioenergetic demands and techniques across different race stages. Speed skating involves both aerobic and anaerobic energy systems, with the balance depending on the event distance—shorter races rely more on anaerobic energy, while longer distances require a significant aerobic component. Effective energy management strategies, such as rapid acceleration and controlled deceleration, are crucial for improving performance.

Injury risks in speed skating, particularly affecting the knees, ankles, spine, legs, and groin, highlight the importance of preventive measures like proper warm-ups, preparatory training, core strength development, and careful training load management. The limited research suggests that elite speed skaters generally have average height and mass, with shorter legs, longer trunks, and well-developed thigh muscles. Lower body fat percentages can also confer a performance advantage, especially for female athletes.

A key contribution of this review is the emphasis on neuromuscular adaptations, such as increased strength and power, which are critical for improving on-ice performance. Strength and power training, including plyometrics and sprinting, enhance force production and efficiency, thus boosting skating speed.

Finally, a balanced conditioning program is essential, combining high-intensity, short-duration training with low-intensity, long-duration work. A periodized training plan, starting with aerobic base building and progressing to specific conditioning like lactate threshold training, ensures that athletes are well-prepared for the various demands of speed skating. This comprehensive approach addresses technical skills, physical conditioning, injury prevention, and strategic energy management, underscoring the multifaceted nature of training in this sport.

4. Accelerating Performance: Reliability of Phase-Specific Measurements in Elite Speed Skaters; 100-meter Starts

Following our review of the current literature on strength training and the development of competitive speed skating (Stuart & Snyman, 2022), the results highlighted the limited literature on the topic and the sport. Speed skating athletes require similar physical qualities (strength, power, coordination, etc.) to their peers in other Olympic time-trial based sports (i.e., swimming, track cycling, and track and field), as well as similar environmental sports such as ice hockey. Additionally, from this review, we determined the most common assessments used in a testing battery for the sport of speed skating to create a general profile of the athlete's abilities that translate to on-ice success (Stuart & Snyman, 2022).

However, a gap in the literature and in this proposed testing battery was the lack of assessments with direct correspondence with on-ice racing performance or directly measuring on-ice measurements associated with the sport skill. Previous research endeavors have shown that the closest of these common assessments is the 30-second Wingate on the cycle ergometer, which has been used as a gold standard within the sport and found to correlate with 1500-meter performance (Hoffman et al., 2017). However, this assessment has proven to lack the necessary sensitivity to effectively measure long-term changes in sprint skating performance (Foster et al., 1993; Vigh Larsen et al., 2020; Zukowski et al., 2023). Additionally, these evaluations are typically conducted at specific phases within the annual training plan, such as summer off-ice training, making them infrequent measurements of these crucial athletic qualities (Hofman et al., 2017).

Previous studies have investigated on-ice acceleration/sprint profiling (Laakso & Secomb, 2023; Lafontaine, 2007; Stenroth et al., 2020; Zukowski et al., 2023), utilizing photoelectric cells, radar technology, and a horizontal robotic resistance device, all of which have shown that split time analysis is a reliable method of assessing essential mechanical factors influencing skating performance at both initial acceleration (0-10 meters) and top speed (0-30 meters) (Stenroth et al., 2020). However, there is a gap in the research on the application, potential monitoring, and evaluation of on-ice acceleration/sprint profiling specifically for competitive speed skaters, who compete in events that cover greater distances than those examined in previous on-ice research.

Therefore, the search for a field-based assessment capable of reliably gauging on-ice sprint performance on a more frequent basis is desirable. This required the development of a reliable test design to meet our specific research questions. Therefore, our subsequent study titled "*Within-Session Reliability of Phase-Specific Measurements Derived from 100-meter Acceleration Profiling in Elite Speed Skaters*" (Stuart et al. 2025) was conducted.

The primary objective of this study was to assess the practical application of 100-meter acceleration profiling in competitive speed skaters by examining the within-session reliability and minimal detectable change (MDC) of mean split times, mean velocity, and mean acceleration measures at distinct phases of the 100-meter speed skating start. Additionally, this study aimed to provide descriptive values of on-ice performance. This involved nineteen elite speed skaters performing two trials on the same day on a 400-meter indoor ice track with split times recorded every 10-meters of 100-meter start using an automated timing system one week prior to the United States 2022 Olympic Trials.

The primary justification behind this study was to establish a reliable protocol for assessing on-ice performance that closely mimics the specificity and demands of competition and to establish this protocol's use in future studies investigating the effects of various postactivation performance enhancement conditioning activities (high-force or high-velocity) on speed skating performance following the results in the subsequent main study (Chapter 5). Ultimately, our extended aim was to contribute valuable insights to the sport of speed skating, potentially influencing the training practices and assessment processes by the integration of the presented findings into the day-to-day training of competitive speed skaters.

The following manuscript has been accepted (January 7th, 2025) to *Measurement in Physical Education and Exercise Science* as an original research article. Therefore, to ensure a seamless integration of the presented work within the entire dissertation thesis document, minor changes have been made to the original formatting of this submitted document. Changes are in accordance with the format specifications of this dissertation thesis document.

Accelerating Performance: Reliability of Phase-Specific Measurements in Elite Speed Skaters; 100-meter Starts

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Abstract:

This study investigated within-session reliability and minimal detectable change (MDC) in mean split time, velocity, and acceleration across 100-meter start phases (0-20, 20-50, 50-70, 70-100-m) in elite speed skaters. Nineteen skaters (10 females, 9 males) completed two trials on the same day on a 400-meter indoor ice track under standardized conditioning, with split times recorded every 10-meteres using an automated timing system. Results showed acceptable reliability for mean split time (ICC = 0.84, CV = 7.5%, MDC = 0.00–0.15 s) and velocity (ICC = 0.79, CV = 9.2%, MDC = 0.21–1.09 m·s−1). Mean acceleration showed moderate reliability (ICC = 0.70, CV = 12.4%, MDC = 0.02–0.10 m/s^^{2}) and higher variability over greater distances (70–100 meters, ICC = 0.65, CV = 15.0%, MDC = 0.03–0.04 m/s^^{2}). These findings support using the 100-meter acceleration profile to assess key performance elements (initial start and sustained acceleration), emphasizing the need to tailor training and assessments to specific race phases.

Keywords: Speed skating, sprinting, assessments, minimal detectable change

Key finding:

- The study demonstrated acceptable within-session reliability for mean split times, velocities, and acceleration during the 100-meter start in elite speed skaters. Key distances (20, 50, and 70 meters) explained 94–100% of the variance in final times, highlighting their importance for monitoring and training.
- Acceleration was most important during the initial 0–20 meters, while maintaining velocity became paramount in later segments (70–100 meters). This highlights the need for tailored performance monitoring strategies across different phases.
- Compared to traditional off-ice assessments, split-time analysis provides a more dynamic and phase-specific measure of sprint performance, enabling frequent and practical monitoring of skaters' technical and physical performance.
- Unlike track sprinting, speed skaters exhibited a progressive velocity increase without a clear peak, likely due to the technical demands of transitioning to the first corner. This underscores the sport-specific nature of acceleration and velocity profiles.
- The findings support using 100-meter acceleration profiling using split-time analysis to guide targeted training interventions (e.g., plyometrics, push-off technique) and suggest potential applicability to other sports requiring high-intensity sprints, such as ice hockey and short-track speed skating.

4.1. Approach to Identifying the Problem

4.1.1. Significance of the 100-meter performance

Long-track speed skating, introduced at the 1924 Chamonix Olympic Winter Games (Houdijk et al., 2003), is a time trial sport performed on a 400-meter indoor oval ice track. Success in sprint events, particularly over 500 and 1,000 meters, relies on skaters' ability to generate high horizontal velocities through substantial force output (de Koning & van Ingen Schenau, 2000; Edwards et al., 2021). The initial 100 meters are critical in determining overall competition outcomes (de Koning et al., 1989). Despite this, much of the existing research has focused on segments of the start phase, such as 0-50 meters, with limited exploration of the entire 100-meter sequence (Song & Moon, 2017; Zukowski et al., 2023). Examining the full 100-meter start offers valuable insights into the transition from initial acceleration to sustained velocity, particularly for events like the 500 meters where maintaining velocity after the acceleration phase is crucial for success (de Koning et al., 1989).

4.1.2. Biomechanics of the Start

The biomechanics of the speed skating start share notable similarities with off-ice track starts, requiring skaters to generate high muscular force to achieve rapid forward acceleration (de Boer et al., 1987; Stuart & Snyman, 2022). The initial push-off predominantly engages the extensor muscles, particularly the gluteus maximus and vastus medialis, to propel the skater forward. High knee extension velocity is a key determinant of effective acceleration performance (Buckeridge et al., 2015; Robbins et al., 2018). The start phase features shorter, quicker strides that gradually transition into longer, gliding strides around the 50-meter mark, typically the point of peak acceleration (de Koning et al., 1989; Stuart & Snyman, 2022).

Throughout the start phase, push-off mechanics, stride length, and ground contact time evolve, playing a pivotal role in maximizing velocity (Van Ingen Schenau, 1992). These kinematic and kinetic factors align with observations in other sports, such as field-based team sport athletes (Clark et al., 2017), track sprinting (Healy et al., 2022), elite speed skating (de Koning & van Ingen Schenau, 2000; Houdijk et al., 2003), and ice hockey (Laakso & Secomb, 2023; Upjohn et al., 2008). Research across these domains underscores the importance of stride mechanics and minimizing ground contact time to enhance sprint performance. These parallels emphasize the critical role of acceleration mechanics in competitive speed skating, where early velocity gains significantly influence sprint event success.

The first 0-20 meters of the start phase are characterized by short ground contact times and high mechanical power outputs (de Koning et al., 1989). The 50-meter mark is crucial as skaters reach maximum acceleration and begin transitioning into the gliding phase, typically starting around 60–70 meters. The gliding phase consists of distinct actions—glide, push-off, and reposition (de Koning & Van Ingen Schenau 2000; Song et al., 2018). Between 70 and 100 meters, skaters demonstrate longer push-offs and increased ground contact times, facilitating sustained acceleration and peak velocities as they approach the first corner (de Koning et al., 1993; Zukowski et al., 2023). At this stage, cornering techniques, race strategy, and physical strength become critical for maintaining or further increasing speed.

Comparisons of sprint performance across skaters of varying skill levels reveal significant differences in split times over the 0–10 meter and 0–30-meter segments, underscoring the importance of acceleration for competitive success (Laakso & Secomb, 2023). Elite skaters tend to exhibit distinctive kinetic and kinematic traits, including optimal pre-extension knee angles, higher work per stroke, increased stroke frequency, greater knee extension velocity, enhanced co-contraction of stabilizing muscles, and more horizontal push-off mechanics (Smith & Roberts 1991; Upjohn et al., 2008). These factors contribute to more efficient energy transfer through the kinetic chain, resulting in higher skating velocities (Upjohn et al., 2008). Consequently, the ability to accelerate effectively is a critical component of speed skating performance, necessitating regular assessment and monitoring (Smith & Roberts 1991).

4.1.3. Research on Acceleration Profiling

Acceleration profiling has been extensively studied in similar sports like track sprinting and ice hockey, but its application to long-track speed skating remains underexplored. While research has examined the mechanics of the start phase (e.g., 0-50 meters), the full 100-meter start in competitive speed skating has received limited attention. Methods such as photoelectric cells and radar technology have been employed in other sports to analyze acceleration mechanics, highlighting the importance of variables like stride frequency, knee extension velocity, and ground contact time (Clark et al., 2017; Haugen et al., 2020; Healy et al., 2022). However, a comprehensive analysis of 100-meter acceleration profiles specific to speed skating could provide valuable insights for talent identification and overall training development.

In sports similar to speed skating, such as ice hockey, split-time analysis has proven to be a reliable method for assessing key mechanical factors affecting initial acceleration (0-10 meters) and top speed (0-30 meters) (Laakso & Secomb, 2023). Despite advancements in on-ice and off-ice profiling in other sports, a gap remains in understanding the application, monitoring, and evaluation of on-ice acceleration specifically for competitive speed skaters, who race over greater distances than those typically studied. Establishing the within-session reliability and correlations between on-ice acceleration metrics and 100-meter performance is essential for creating effective testing protocols to guide athlete development and talent identification (Weakley 2023).

Furthermore, determining the minimal detectable change (MDC) in on-ice acceleration profiling, including mean split times, velocity, and acceleration would offer critical insights into actual performance improvements resulting from training. Identifying these metrics across different phases of the 100-meter start could enhance understanding of a skater's acceleration capabilities, preparation for corner entry, and performance through corners.

4.1.4. Primary aim of manuscript

Despite research on acceleration profiling in other sports (Clark et al., 2017; Edwards et al., 2021; Haugen et al., 2020; Healy et al., 2022; Laakso & Secomb, 2023; Lafontaine, 2007; Perez et al., 2022; Samozino et al., 2016; Stenroth et al., 2020), a gap remains in understanding these dynamics in speed skating. Given this context, a comprehensive analysis of acceleration profiles over the full 100-meter distance would be important for developing effective testing protocols for talent identification and enhancing training strategies in speed skating (Weakley et al., 2023). To address this gap, the aim of this study was to assess the within-session reliability and minimal detectable change (MDC) of acceleration, velocity, and split-time measures during the 100-meter start in competitive speed skaters. We hypothesized that these measures would show high reliability and strong correlations with final 100-meter times, given the skill levels of the skaters involved.

4.1.5. Methodologies

4.1.5.a. Subjects

Nineteen elite/world class 500-meter speed skaters 10 females (168 cm $\pm$ 3.4 cm, 65.1 kg $\pm$ 4.8 kg) and 9 males (180.5 cm $\pm$ 9.2 cm, 78.6 kg $\pm$ 10.5 kg), each preparing for the 2022 Olympic Trials, participated in this study. Participants met the following criteria: (a) national or international elite status, (b) minimum Olympic qualifying times, and (c) no lower limb injuries or mobility impairments affecting participation. Given the rarity and exclusivity of this high-performance population, an a priori sample size estimation was not used, which aligns with studies on elite athletes where sample size is often limited by athlete availability yet still provides valuable insights specific to this level of competition (McKay et al., 2022). All subjects were informed about the potential risks and benefits of the procedures and signed a written informed consent form which was approved by a university ethics board (Appendix #7).

4.1.5.b. Procedures

Prior to the start of data collection, all participants performed a standardized warm up of various lower limb calisthenic exercises and skating specific warm up. Participants were already familiarized with the 100-meter start as part of their normal training and competitive event. Following the initial warm-up process, approximately five minutes of rest was given to allow sufficient time to provide instruction to all subjects. Subsequently, participants then performed a self-selected dryland and on-ice warm up, with specific skating technique drills, followed by a brief, self-selected rest period.

For maximal effort trials, participants were instructed to focus on accelerating through the entirety of the 100-meters. Each participant adopted a self-selected starting position with blades positioned behind the 0-meter start line to ensure consistency with competition standards and prevent prematurely triggering the initial timing gate (Laakso & Secomb 2023). To eliminate the influence of reaction time, participants began each sprint effort at their own convenience (Edwards et al., 2021). Verbal encouragement was provided to maximize effort. Each participants completed two 100-meter maximal sprint trials, with a self-determined rest period ranging from 6-8 minutes between trials to allow for adequate recovery and mitigated potential fatigue effects on reliability measures.

In line with previous research (Haugen et al., 2020), photoelectric timing gates (TCi System, Brower Timing Systems, Draper, UT) were positioned every 10-meters from 0- to 100-meter along the 100-meter straightaway of the 400-meter oval. The timing gates were set to 41 centimeters above the ice surface to trigger accurately when the athlete’s blade crossed each beam (Laakso & Secomb 2023). Each 10-meter split time of the 100-meter profile was categorized into four distinct acceleration phases, as recommended by prior studies: (a) *Immediate acceleration* (0-20-meters), also known as the running phase and the key acceleration phase in speed skating (Song & Moon, 2017); (b) *Acceleration mid-point* (20-50-meters), marking the transition between the running and gliding phases; (c) *Preparation for corner entry* (50-70-meters) where skaters begin gliding with longer push-off to maintain acceleration and reach top speed (de Koning et al., 1993; Zukowski et al., 2023); and (d) *Corner entry* (70-100-meters), including the 100-meter split, as the skater enters the first corner of the race (Clark et al., 2017; Healy et al., 2022). To assess within-season reliability, the mean split time from the two trials was used, following previously established protocols (Edwards et al., 2021; Haugen et al., 2020).

Testing conditions simulated competitive settings, with ice temperature at −8.4°C, air temperature at 14.7°C, and 29% humidity. All testing occurred on a single day under these consistent conditions to minimize external variability.

4.1.5.c. Data Collection

A repeated-measures design was employed to assess within-session reliability of 100-meter start performance measures, focusing on mean split times (s), velocities (m·s−1), and accelerations (m/s^2). Each participant completed two maximal-effort trials in a single session, and the averages were analyzed. No test-retest interval was required as performance was measured within-session to capture true variability, not external factors. Since the velocity specifically at the 10-meter split was important, the mean velocity at each split was calculated as the average of the prior 10-meters average split time and the subsequent 10-meters average split time (Equation 1).

Equation 1. 10-m Split Velocity

$$10 - \text{m Split Velocity} = \frac{\frac{(d_{10}-d_0)}{(t_{10}-t_0)} + \frac{(d_{20}-d_{10})}{(t_{20}-t_{10})}}{2} \quad (1)$$

Because there was no measurement taken when i > 100-meter, only the average split from 90-meter to 100-meter was used to estimate the mean velocity at 100-meters (Equation 2).

Equation 2. 100-m Split Velocity

$$100 - \text{m Split Velocity} = \frac{(d_{100}-d_{90})}{(t_{100}-t_{90})} \quad (2)$$

Mean acceleration was calculated as a change in average velocity over the change in average split time of the previous 10-meters (Equation 3). This allowed for the understanding of the mean acceleration up to the split in question following the preceding split distance. All data were collected and imported into Microsoft Excel (Microsoft Corporation, Redmond, WA) and prepared for further confidential analysis and calculations.

Equation 3. 10-m Split Average Acceleration

$$\text{Average Acceleration} = \frac{(v_{10} - v_0)}{(t_{10} - t_0)} \quad (3)$$

4.1.5.d. Statistical Analysis

A customized spreadsheet (Hopkins 2015) was used for statistical analysis. Relative reliability was assessed using two-way mixed intraclass correlation coefficients (ICC 2,1) and coefficients of variation (CV) were calculated with 95% confidence intervals (CI) (Hopkins 2000; Hopkins 2017). The standard error of measurement (SEM) was used to assess how much the individual performance measures might vary due to measurement error and was calculated as $SEM = SD \bullet \sqrt{(1 - ICC)}$. A 95% threshold was utilized to imply more certainty that the observed change in on-ice performance was not due to measurement error or random fluctuation due to ice or track conditions and to provide a higher degree of confidence to mitigate the risk of making a Type I error and was calculated as $1.96 \times SEM \times \sqrt{2}$.

Data quality was continuously monitored, and any technical issues with timing gates were promptly resolved. Cases with missing data due to malfunctions were excluded, constituting less than 5% of the data set. Listwise deletion was used, as missing data were minimal and did not impact the overall analysis. There was no follow-up in this study as all 19 subjects completed both trials. Furthermore, no formal sensitivity analyses were performed in this study due to the homogeneity of the sample and consistency in the environmental conditions.

Reliability Analysis

Reliability was evaluated in terms of both relative and absolute reliability (Table 2). Relative reliability thresholds, as described by Hopkins (2004) and McGuigan (2017), were categorized as follows: ICC values between 0.20–0.49 indicate low reliability, 0.50–0.74 moderate reliability, 0.75–0.89 high reliability, 0.90–0.98 very high reliability, and values greater than 0.99 indicate extremely high reliability. Absolute reliability was considered acceptable if the CV was ≤ 10%. Consistent with previous research on on-ice and off-ice sprint profiling (Edwards et al., 2021; Healy et al., 2022), performance measures were interpreted as having acceptable reliability if ICC ≥ 0.75 and CV ≤ 10%, moderate reliability if ICC < 0.75 and CV ≤ 10%, and poor reliability if ICC < 0.75 and CV > 10%.

Validity Analysis

To further explore the validity of the acceleration phases, Pearson correlation coefficients (r) and coefficients of determination (R^2) were employed to examine the relationships between variables derived from the four phases of the 100-meter acceleration profile and the final 100-meter time (Table 3). This approach enabled the identification of key performance measures that correlated the strongest with final sprint times, thereby strengthening the validity of these as indicators of elite sprint performance. The magnitude of correlations was interpreted according to standard thresholds (Hopkins et al., 2009), categorized as trivial (0–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), near perfect (0.90–0.99), and perfect (1.00).

Minimum Detectable Change (MDC)

The MDC was calculated to quantify the smallest change in performance that can be considered beyond measurement error. MDC was computed as:

$1.96 \times SEM \times \sqrt{2}$.

Considerations of Confounding Factors

To control for confounding factors, all participants received standardized warm-ups, and environmental conditions were maintained. Males and females were grouped together in all analyses.

4.2. New Additions to the Existing Literature

The present manuscript (Stuart et al. 2025) aimed to explore the reliability and relationship of 100-meter acceleration profiling with final time in competitive speed skaters. While prior research has examined the start phase up to 50 meters, this study extends the analysis to the entire 100-meter start. This is significant because sustaining acceleration beyond 50 meters is critical in speed skating, where transitioning from an explosive start to peak velocity can determine overall competition placement (de Koning et al., 1989; Song & Moon, 2017). To our knowledge, this is the first investigation of within-session reliability for on-ice performance measures across the full 100-meter start, providing novel insights into acceleration variability and its potential implications for training and performance in elite speed skating.

Our findings demonstrated acceptable reliability for mean split time and mean velocity, with near-perfect positive and negative correlations with 100-meter final time across all phases, respectively (Table 8 and Table 9). Mean acceleration at 20 meters exhibited moderate within-session reliability and a near-perfect negative correlation with 100-meter final time; however, variability increased in later phases (20–50, 50–70, and 70–100 meters) (Table 9). These results underscore the dynamic nature of speed skating and the necessity for phase-specific performance monitoring strategies, such as maximizing high force outputs during the initial 20 meters, improving the transition from acceleration to higher velocities between 20–70 meters, and sustaining velocity effectively from 70–100 meters.

Table 8. Within-Session Reliability of On-ice Performance Measures

	0-20-meter	20-50-meter	50-70-meter	70-100-meter
Mean Split Times (s)				
Mean ± SD	3.37 ± 0.19	6.51 ± 0.43	8.34 ± 0.55	10.90 ± 0.73
$ICC^{95\%}$	0.97 [0.89, 0.99]	0.99 [0.96, 1.00]	0.99 [0.97, 1.00]	1.00 [0.99, 1.00]
$CV^{95\%}$	6% [5.90, 6.10]	7% [6.77, 7.23]	7% [6.70, 7.30]	7% [6.60, 7.40]
SEM	0.03	0.04	0.06	0.07
$MDC^{95\%}$	0.10	0.12	0.15	0.20
Mean Velocity (m·s−1)				
Mean ± SD	8.36 ± 0.62	10.61 ± 0.77	11.32 ± 0.82	11.93 ± 0.90
$ICC^{95\%}$	0.96 [0.88, 0.99]	0.99 [0.98, 0.99]	0.98 [0.94, 0.99]	0.81 [0.48, 0.94]
$CV^{95\%}$	8% [7.66, 8.34]	8% [7.58, 8.42]	8% [7.55, 8.45]	8% [7.51, 8.49]
SEM	0.12	0.08	0.12	0.39
$MDC^{95\%}$	0.35	0.21	0.32	1.09
Mean Acceleration (m/s ^2)				
Mean ± SD	0.62 ± 0.11	0.10 ± 0.02	0.04 ± 0.01	0.00 ± 0.01
$ICC^{95\%}$	0.88 [0.65, 0.96]	0.73 [0.33, 0.91]	0.05 [-0.49, 0.57]	-0.19 [-0.65, 0.39]
$CV^{95\%}$	18% [17.94, 18.06]	15% [14.99, 15.01]	30% [29.99, 30.01]	114% [113.99, 114.01]
SEM	0.04	0.01	0.01	0.01
$MDC^{95\%}$	0.10	0.02	0.03	0.04

$ICC^{95\%}$ = intraclass correlation at 95% confidence interval
$CV^{95\%}$ = coefficient of variation at 95% confidence interval
SEM = Standard Error of Measurement
$MDC^{95\%}$ = Minimum Detectable Change at 95% confidence interval

Table 9. Correlation and coefficient of determination between mean split time, mean velocity, and mean acceleration with 100-m final time.

	Mean Split Time			Mean Velocity			Mean Acceleration		
Split Distance	***r***	**95% CI**	**R^2**	***r***	**95% CI**	**R^2**	***r***	**95% CI**	**R^2**
0-20-meters	0.970§	[0.901, 0.991]	0.94	-0.985§	[-0.948, -0.996]	0.97	-0.960§	[-0.988, -0.867]	0.92
20-50-meters	0.994§	[0.980, 0.998]	0.94	-0.993§	[-0.975, -0.998]	0.99	-0.678†	[-0.895, -0.202]	0.46
50-70-meters	0.998§	[0.992, 0.999]	1.00	-0.992§	[-0.972, 0.998]	0.98	-0.614†	[-0.870, -0.095]	0.38
70-100-meters	1.00§	[0.999, 1.000]	1.00	-0.937§	[-0.797, -0.981]	0.88	0.046	[-0.518, 0.582]	0.00

§ $p<0.001$
†$p<0.05$

Traditionally, off-ice laboratory tests, such as the Wingate protocol on a cycle ergometer, have been used to assess on-ice sprint performance in speed skating (Hofman et al., 2017; Smith & Roberts 1991). However, these assessments often lack the sensitivity needed to effectively measure long-term changes in speed skating performance (Foster et al., 1993; Van Ingen Schenau 1992; Zukowski et al., 2023). Additionally, these evaluations are typically conducted at specific phases within the annual training plan, such as summer off-ice training, resulting in infrequent measurements of these crucial athletic qualities (Hofman et al., 2017; Thompson et al., 2003). Thus, the need for a field-based assessment capable of reliably gauging on-ice sprint performance more frequently, offers distinct advantages for the ongoing development and monitoring of competitive speed skating athlete (Weakley et al., 2023). In contrast to the limited scope of off-ice assessments, split-time analysis allows practitioners the ability to capture performance across each phase, particularly in the initial acceleration and top speed phases.

Previous research has demonstrated the reliability of split time analysis in assessing mechanical factors affecting sprint skating performance during initial acceleration (0-10 meters) and top speed (0-30 meters) (Stenroth et al., 2020). Our findings align with this prior research, as mean split time exhibited acceptable reliability across all phases of the 100-meter profile. Notably, splits at 20-, 50-, and 70-meters explained 94-100% of the 100-meter final time, underscoring the importance of monitoring these distances in training sessions. Our study expands the application of on-ice profiling through split time analysis in speed skating, suggesting its reliable use in assessing performance beyond 30-meters, similar to its application in track and field and team sports (Clark et al., 2017; Healy et al., 2022; Samozino et al., 2016). Beyond split times, mean velocity at various distances provides another reliable measure to assess sprinting technique and identify potential limitations.

Additionally, mean velocity demonstrated acceptable reliability with near-perfect negative correlation at all split distances. Specifically, mean velocity at 50- and 70-meters explained 99% and 98% of the 100-meter final time, respectively. This indicates the importance of these split distances in identifying sprinting technique; a drop in mean velocity or failure to reach a high percentage of maximum velocity at these segments may indicate performance limitations. Monitoring these phases can help coaches determine if an athlete requires technical proficiency improvements, which could involve refining push-off technique or employing off-ice methods such as plyometric training that include deep squats (full range of knee flexion and extension) and/or modified calf raise exercise (Lafontaine 2007; Song & Moon, 2017).

It is important to note, unlike off-ice sprinting in track and field, where athletes typically reach peak velocity during the middle phase of the 100-meter sprint and experience gradual deceleration toward the end (Healy et al., 2022), speed skaters appear to maintain a progressive velocity increase without achieving a distinct peak during the 100-meter start (Table 10). This pattern may reflect the technical and tactical demands specific to speed skating, particularly the need to prepare for the tighter corner entry radius at the apex of the first turn (150 meters) and the corner exit at 200 meters in the 500-meter race. These findings suggest that the acceleration and velocity profiles in speed skating are shaped by the unique requirements of the sport. While mean velocity highlights the importance of maintaining speed through the start, acceleration at specific segments, such as the 0-20-meters, is equally critical to an effective sprint performance.

Table 10. Descriptive Statistics of 100-meter profiling in Male and Female speed skaters

	Male (n= 9)	**Female (n= 10)**
Subjects		
Height (cm)	180.5 ± 9.1	168 ± 3.3
Body mass (kg)	78.6 ± 10.5	65.1 ± 4.8
Body fat (%BF)	12.35 ± 3.7	22.0 ± 5.3
Skill Level	Junior = 3 / Senior = 6	Junior = 4 / Senior = 6
Competitive Experience	International = 4 / National = 5	International = 7 / National = 3
On-ice Performance		
100m (s):	10.07 ± 0.55	11.35 ± 0.46
Max Velocity ($m{\cdot}s{-}1$)	12.87 ± 0.40	11.35 ± 0.63
Vmax 20-m %	69.4 ± 2.8	70.4 ± 1.2
Vmax 50-m %	87.8 ± 2.8	89.1 ± 1.3
Vmax 70-m %	93.8 ± 2.5	95.0 ± 1.5
Vmax 100-m %	99.8 ± 0.2	99.4 ± 1.2
Max Acceleration ($m/s^{\wedge 2}$)	3.44 ± 0.27	2.82 ± 0.18

m= meters
cm= centimeters
kg = kilograms
%BF = percent body fat
s = seconds
ms = milliseconds
Vmax % = percentage of maximum velocity at split
m/s^2 = meters per second squared

Our findings also support previous research emphasizes the critical role of acceleration, particularly in the initial segments of the 100-meter start (de Koning et al., 1992; de Koning et al., 2005). Mean acceleration at 20-meters demonstrated moderate reliability and accounted for

92% of the 100-meter final time. However, the observed poor reliability and low correlation with 100-meter final time suggest that as skaters transition from the initial sprinting phase to the gliding phase in anticipation of the corner, the emphasis on acceleration may diminish. Instead, maintaining speed through efficient push-offs becomes paramount, as indicated by the rate of change decreasing as the distances increase. Therefore, examining the mean acceleration during the initial 0-20 meters is essential for coaches to assess a competitive speed skater accelerative ability, facilitating targeted off-ice strength and conditioning programs that incorporate maximal strength and power-based exercises and/or specific skill transfer drills (dryland) to maximize on-ice proficiency. Although our findings are rooted in competitive speed skating, the principles of acceleration and force application may hold value for other sports.

The findings of this study, focused on the reliability and performance of acceleration profiles in elite speed skaters, are primarily applicable to similar populations with high skill levels, such as international or national-level athletes. The consistency of environmental conditions and the specificity of the 100-meter sprint skating task suggest that the results are most generalizable to long-track speed skaters competing in sprint events. However, the underlying biomechanical principles of acceleration and force generation may be relevant to other sports requiring high-intensity sprint efforts, such as ice hockey, track sprinting, and short-track speed skating, where acceleration and sprint performance are critical. Further studies are needed to confirm whether these findings extend to different competition levels, age groups, or other sport contexts. While these insights provide a foundation, the study's limitations underscore the need for broader research across varying skill levels and environmental conditions.

Similar to all research, this study has limitations. Despite efforts to simulate competitive conditions, participants did not perform trials in racing conditions (i.e., racing in pairs, audible start command). Furthermore, participants were instructed to prioritize acceleration throughout the 100-meters, which may have altered their technical and tactical approach in anticipation of the tighter corner entry radius. While the participants were highly trained, skill level can significantly differentiate skaters (Van Ingen Schenau 1987; Upjohn et al., 2008). Future studies should replicate this design with a larger and more diverse sample, to reduce outliers, enable sex-specific analysis, and facilitate examination across skill subcategories (e.g., low/high caliber or slower/faster skaters). The findings of the present study support a tailored approach to acceleration monitoring that can guide training specificity, while further research could examine how these measures influence broader performance outcomes in the 500-meter competition.

In conclusion, this study supports the use of the 100-meter acceleration profile for the development and potential monitoring of competitive speed skaters. The results allow coaches to establish the minimal detectable change (MDC) in on-ice sprint performance measures (mean split times, mean velocity, and mean acceleration) at specific key phases (20-, 50-, 70-, and 100-meters) of the 100-meter start (Weakley et al., 2023). This provides a better framework for assessing, ranking, and prescribing training for athletes. However, the study emphasizes the necessity for performance monitoring strategies tailored to the different phases of the start, as not all measures may be suitable for the entirety of the 100-meter profile.

4.3. Practical Significance

The results of this study provide actionable insights for coaches and practitioners by establishing reliable metrics for assessing athlete performance during the 100-meter start (Table 10). Importantly, these findings are not only applicable to elite-level skaters but also hold potential for adaptation in youth and amateur programs. For younger athletes, simplified timing systems could offer an accessible means of introducing acceleration profiling to aid in talent identification and foundational skill development.

Table 11. 100-m practical application

Phase (meters)	Key Metrics	Reliability (ICC, CV%)	Correlation with Final Time (R^2)	Practical Application
0-20	Mean Acceleration	Moderate (0.75, 5%)	0.92	Emphasize maximal strength and explosive power training to enhance early acceleration.
20-50	Mean Velocity	High (0.95, 3%)	0.99	Focus on maintaining velocity with technical refinement in stride length and push-offs.
50-70	Mean Velocity	High (0.94, 4%)	0.96	Ensure efficient transition between acceleration and top speed; refine skating mechanics.
70-100	Mean Split Time	High (0.94, 4%)	0.94	Monitor sustained velocity to inform cornering specific preparation.

4.4. Future Research Direction

Building on these findings, future research should examine the influence of targeted acceleration and cornering techniques on 500-meter performance. Specifically, future acceleration studies should investigate how maximizing force application in the 0–20-meter phase affects transitions to the corner apex (150 meters) and corner exit (200 meters). Research could explore the biomechanical demands of corner entry and exit, including lean angles, force application asymmetries, and the role of stabilizing musculature in maintaining velocity through turns. Future studies should also evaluate how these profiling methods can be adapted for younger or less experienced athletes to guide talent identification and progressive training programs.

5. Investigating the Consistency in Countermovement Jump Performance Following High Velocity and High Force PAPE: a Multi-day Analysis.

In the first manuscript of this dissertation thesis (Chapter 4), a review of the current existing literature on the essential aspects of competitive speed skating facilitated the groundwork for developing comprehensive strength and conditioning programs. From this review (Stuart & Snyman, 2021), it can be elucidated that speed skating shares similar pre-competition strength and conditioning training principles with many other power-based sports. A commonly used methodology that spans across these different sports is postactivation performance enhancement (PAPE).

For decades, strength and power training methodologies such as postactivation performance enhancement have been widely used by professionals aiming to increase power output for their athletes. In practice, this is usually done via potentiating complexes, which, in the sport of speed skating, have been beneficial at enhancing the training effects on short-distance skating performance (Wen-Lan Wu, 2016). A potential rationale for this training effect may be the enhancement of the nervous system through more power and ballistic-type training while retaining maximal strength through low volume and moderate intensity (80-85% 1RM) (Stuart & Snyman, 2022).

The body of research suggests that this method provides general results to athletes on average; however, it is often claimed that PAPE is a highly individualized response, with some authors claiming that stronger individuals can potentiate faster, requiring more intense conditioning activities and potentiating to a greater degree than their weaker counterparts (Chiu et al., 2003; Seitz & Haff, 2015; Wilson et al., 2013). Despite these individualized claims, the predictability of PAPE timing has not yet been determined. Therefore, it is possible that PAPE is not an individualized phenomenon but may be a random effect that occurs as a result of a myriad of factors, not just the conditioning activity and the time interaction of fatigue and potentiation. Additionally, previous research has only investigated single experimental PAPE sessions without repeatedly performing the same protocols with the same individuals over time, making it difficult to know if or when enhanced performance will repeatedly occur over multiple training sessions.

Therefore, our study titled "*Investigating the Consistency in Countermovement Jump Performance Following High Velocity and High Force PAPE: a Multi-day Analysis.*" (Stuart et al., 2024) was conducted. The primary objective of this study was to determine if PAPE (i.e., using a high-velocity conditioning activity and a high-force conditioning activity) is repeatable within individuals across multiple experimental sessions. Additionally, a secondary purpose of this study was to determine if PAPE could be accurately predicted across multiple sessions by employing "individualized" timing.

Originally, two separate and independent (yet very similar) studies were conducted; both were within-subject study designs that investigated the predictability of band-assisted countermovement jump (BACMJ) and isometric squat (ISOSQ) to improve acute jumping performance. However, after completing both studies and analyzing the data, the decision was made to combine both studies into a single paper with a common theme.

In the initial proposal of this dissertation thesis, the goal was to investigate the effect of different (static and dynamic) PAPE protocols and their influence on speed skating performance using the 100-meter acceleration profiling protocol established in our previous study (Chapter 6). This would allow for a more appropriate PAPE intervention as it mimics the demands of the sport, such as producing force quickly from a somewhat static or fully static position through the rotation of the hips and body, transferring lateral forces into forward movement, not just movement common to the weight room (i.e., vertical jump) (Bonfim Lima et al., 2011; Seitz & Haff, 2017).

However, after reviewing the results of the present manuscript, it was determined that there is an inconsistent pattern of within-subject potentiation when examining across multiple experimental sessions, highlighting the difficulty of achieving consistent PAPE effects within individuals over time." These results emphasize the challenges of replicating PAPE responses in individuals over time. Therefore, it was determined that it was unnecessary to proceed with the original proposal, as subsequent studies may produce similar results.

This manuscript was accepted on December 30th, 2024, in the Journal of Strength and Conditioning Research as original research (Appendix #1). The substantive content of the manuscript remains unchanged. However, modifications have been made to the original document's formatting to ensure consistency throughout the dissertation thesis. Minor changes have been made to the original formatting of this submitted document.

Investigating the Consistency in Countermovement Jump Performance Following High Velocity and High Force PAPE: a Multi-day Analysis.

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Original research

Abstract

Post-activation performance enhancement (PAPE) is widely acknowledged in both practical application and research. However, studies have primarily focused on single experimental PAPE sessions, neglecting the repeatability of protocols with the same individuals over time. The purpose of this study was to determine if PAPE, involving high-velocity and high-force conditioning activities, could be observed at consistent time points across multiple sessions. Sixteen elite speed skaters (9 males: 23.1 ± 2.6 yrs. and 7 females: 24.2 ± 4.7 yrs.) participated in six sessions for each independent study. For all sessions, a standardized warm-up was performed, followed by three baseline bodyweight countermovement jumps (CMJ), and a potentiation protocol of five repeated band-assisted countermovement jumps (BACMJ) at approximately 20% bodyweight reduction, or a single 5-second maximal effort isometric squat (ISOSQ). Subsequently, subjects rested for 3-, 5-, and 7-minutes before performing a single bodyweight CMJ at each time point. Multi-day analyses of variance showed mixed results for both protocols, with most effect sizes ranging from trivial to small. Linear mixed models indicated that at the individual level, subjects did not consistently jump higher at any specific post-PAPE rest time. The variance between baseline and post-PAPE JH at the rest time that produced the greatest result was neither statistically significant nor statistically different ($p > 0.05$), compared to other rest times. PAPE was identifiable across sessions but variability in jump performance and inconsistent effects made it difficult to observe repeatable responses within individuals over time, thus questioning the idea of “individualizing” PAPE in practice.

Keywords: post activation performance enhancement, isometric squat, band assisted countermovement jumps, power, jump height

Key finding:

- The present study demonstrates that PAPE effects were observed inconsistently across multiple experimental sessions. Jump height (JH) improvements were evident in only one out of six sessions for the Band-Assisted Countermovement Jump (BACMJ) and two out of six sessions for the Isometric Squat (ISOSQ), with trivial to small effect sizes, except for the 3-minute rest time in a single ISOSQ sessions.
- While traditional ANOVA methods yielded mixed results, highlighting limited repeatability and aligning with prior research thus suggesting challenges in identifying PAPE responses within individuals over time.
- Attempts to predict an "optimal" rest time point for individualized PAPE responses showed no consistent enhancements. Performance variance at specific rest times (3-, 5-, 7-minutes) was comparable to baseline variance, and individualized timing produced no statistically significant advantages over random rest times.

5.1. Approach to Identifying the Problem

Post-activation performance enhancement (PAPE) refers to the improvement in maximal strength, power, or speed following a conditioning activity that typically involves high-velocity or high-force muscle contractions (Prieske et al., 2020). Strength and conditioning professionals frequently utilize PAPE to boost athletes' power output. This is commonly achieved through potentiating complexes, which consist of a heavy (resisted) or light (assisted) load exercise that is biomechanically similar to a subsequent plyometric exercise (Prieske et al., 2020). As a result, the performance in the plyometric exercise can be enhanced compared to if it were performed without the preceding conditioning activity (Prieske et al., 2020). The mechanisms underlying this acute performance enhancement are not fully understood but are thought to involve factors such as the phosphorylation of myosin regulatory light chains (Blazevich & Babault 2019; Boullosa et al., 2018; Docherty & Hodgson 2007; Rassier & Macintosh 2000; Tillin & Bishop 2009), increased recruitment of higher-order motor units (Docherty & Hodgson 2007; Prieske et al., 2020; Rassier et al., 2000; Tillin & Bishop 2009), changes in muscle pennation angle (Rassier et al., 2000; Tillin & Bishop 2009), or a combination of these factors (Rassier et al., 2000; Sale 2002; Tillin & Bishop 2009). Regardless of the exact mechanisms, these potentiating complexes are widely used in strength and conditioning programs. Various studies have explored different acute PAPE protocols, including maximal voluntary isometric contractions (French & Kraemer, 2003; Gossen & Sale 2000; Gullich & Schmidtbleicher 1996) and assisted jumping exercises (Cazas et al., 2013; Markovic & Jaric 2007; Tufano et al., 2018b), to understand their effects.

5.1.1. High Force PAPE (Isometric Squat)

Research has shown that high-force PAPE can enhance neuromuscular activation and explosive force, leading to improvements in jump height (JH), maximal force output, and acceleration impulse (French & Kraemer, 2003). This makes maximal voluntary isometric contractions, such as the isometric squat (ISOSQ) (Figure 3), a viable tool for strength and conditioning practitioners, as they can improve force production through increased motor unit recruitment (Docherty & Hodgson 2007; Prieske et al. 2020; Rassier & Macintosh 2000; Tillin & Bishop 2009) and enhanced muscle fiber activation (Rassier & Macintosh 2000; Sale 2002; Tillin & Bishop 2009) at specific joint angles relevant to athletic movements such as sprinting, jumping, or change of direction (Tillin & Bishop 2009; Tillin et al., 2012).

Figure 3. Demonstration of Isometric Squat (ISOSQ)

5.1.2. Assisted Plyometric PAPE (Band Assisted Countermovement Jumps)

Conversely, assisted plyometric PAPE protocols, such as assisted repeated jumps (Figure 4), can acutely enhance power output by decreasing the athlete's bodyweight, resulting in an over-speed effect that appears to carry over into faster subsequent bodyweight movements when utilized in a postactivation complex (Darmiento et al., 2012; Markovic & Jaric 2007; Tufano et al., 2018b). These jumps are classified as "slow plyometric" (contact time >250 milliseconds) in nature (Tufano et al., 2018b). As the band stretches during the countermovement phase, the level of assistance increases, potentially leading to greater countermovement depth (Tufano et al., 2018b) and as a result, increased jump height, longer flight time (Tillin et al., 2012; Tran et al., 2011), and higher take off velocity (Cazas et al., 2013) due to the reduced body weight. However, the benefits of greater countermovement depth depend on other factors, such as rate of force development (RFD), neuromuscular coordination, and the elastic properties of the band, which impact takeoff forces (Tufano et al., 2018). Although previous researchers have not directly compared high force vs. high velocity PAPE protocols in the same study, both PAPE protocols have been shown to acutely enhance qualities that are associated with athletic performance in mean group responses (Darmiento et al., 2012; French & Kraemer 2003; Kilgallon & Beard 2010; Tillin et al., 2012; Tufano et al., 2018a); however, the variability in individual responses prompts further investigation.

Figure 4. Demonstration of Band Assisted Countermovement Jumps

5.1.3. Recommendations for Individualization of PAPE

It is generally accepted in both practical and research settings that PAPE should be individualized (Scott et al., 2018; Tillin & Bishop 2009). This recommendation is often made because studies have found two main outcomes: (a) there are "responders and non-responders," meaning some individuals experience performance gains while others do not (Rixon et al., 2007, Scott et al., 2018; Smith et al., 2001); and (b) that PAPE should be individualized based on many different factors such as the external loads applied (Dolan et al., 2017; Fukutani et al., 2014; Kartages et al., 2019; Kilgallon & Beard 2010; Mina et al., 2016), the rest period length (Cazas et al., 2013; Prieske et al., 2020), training age (Chiu & Salem 2003), relative strength levels (Chiu & Salem 2012; Seitz et al., 2014), and gender (Rixon et al., 2007), as these factors influence the physiological balance between potentiation and fatigue. It has been suggested that individuals with higher relative strength may recruit more motor units and experience greater potentiation but may require longer recovery to prevent excessive fatigue from heavier loading

(Chiu & Salem 2012; Dolan et al., 2017; Fukutani et al., 2014; Kartages et al., 2019; Kilgallon & Beard 2010; Mina et al., 2016; Seitz et al., 2014). Similarly, rest periods that are too long or short can interfere and diminish potentiation effects (Cazas et al., 2013; Prieske et al., 2020). Additionally, it has been suggested that gender and training age can impact the rate of recovery and potentiation responses due to hormonal responses, neuromuscular efficiency, and muscle fiber composition differences (Chiu & Salem 2003; Rixon et al., 2007). It has been suggested that gender-related differences such as hormonal fluctuation (i.e., estrogen and progesterone) across the menstrual cycle may influence PAPE response in women (Rixon et al., 2007). As such, researchers recommend an individualized optimal recovery window based on these factors to maximize performance while minimizing fatigue (Gullich & Schmidtbleicher 1996; Scott et al., 2018). However, the consistency of performance improvements within individuals over time remains unclear.

The idea of individualizing PAPE would be beneficial for strength and conditioning professionals. However, in practice, it remains challenging because it is unclear if or when enhanced performance consistently occurs across multiple training sessions. Most research has focused on single experimental PAPE sessions without repeatedly testing the same protocols with the same individuals over time. These studies often use repeated measures ANOVA to analyze group-level differences, identifying time points where the group's average PAPE performance exceeds baseline (Scott et al., 2018). While this approach has limitations, some research attempted to individualize PAPE by examining the phenomenon at the individual level using similar statistical methods. However, the assumption that individuals will experience PAPE at specific time points has not been tested for repeatability. If PAPE could be individualized, it would be expected that (a) maximum jump height would occur at the same time point on different days for each individual, (b) the variance in post-PAPE jump performance would exceed baseline performance variance (e.g., 5% versus 4%), and (c) the jump height at the individualized optimal time point would be greater than at a random time point. To the best of the authors' knowledge, these assumptions have not been thoroughly investigated in prior research.

5.1.4. Primary aim of manuscript

Thus, the primary aim of this manuscript (Stuart et al. 2024) was to determine whether PAPE (through high-velocity and high-force conditioning activities) is repeatable across multiple sessions for individuals. A secondary aim was to determine if PAPE could be accurately predicted post-hoc across multiples sessions by employing individualized timing based on the data collected throughout the sessions. Based on previous studies (Cazas et al., 2013; Cazas-Moreno et al., 2021; Chatzopoulos et al., 2007; Chiu et al., 2003; Chiu & Salem 2012; Scott et al., 2018; Seitz et al., 2014), we expect that PAPE will be observed at the group level using repeated measures ANOVA. However, we hypothesize that neither PAPE protocol will reliably predict or enhance jump performance across multiple sessions, as individual responses to conditioning activities will be inconsistent (Figure 5).

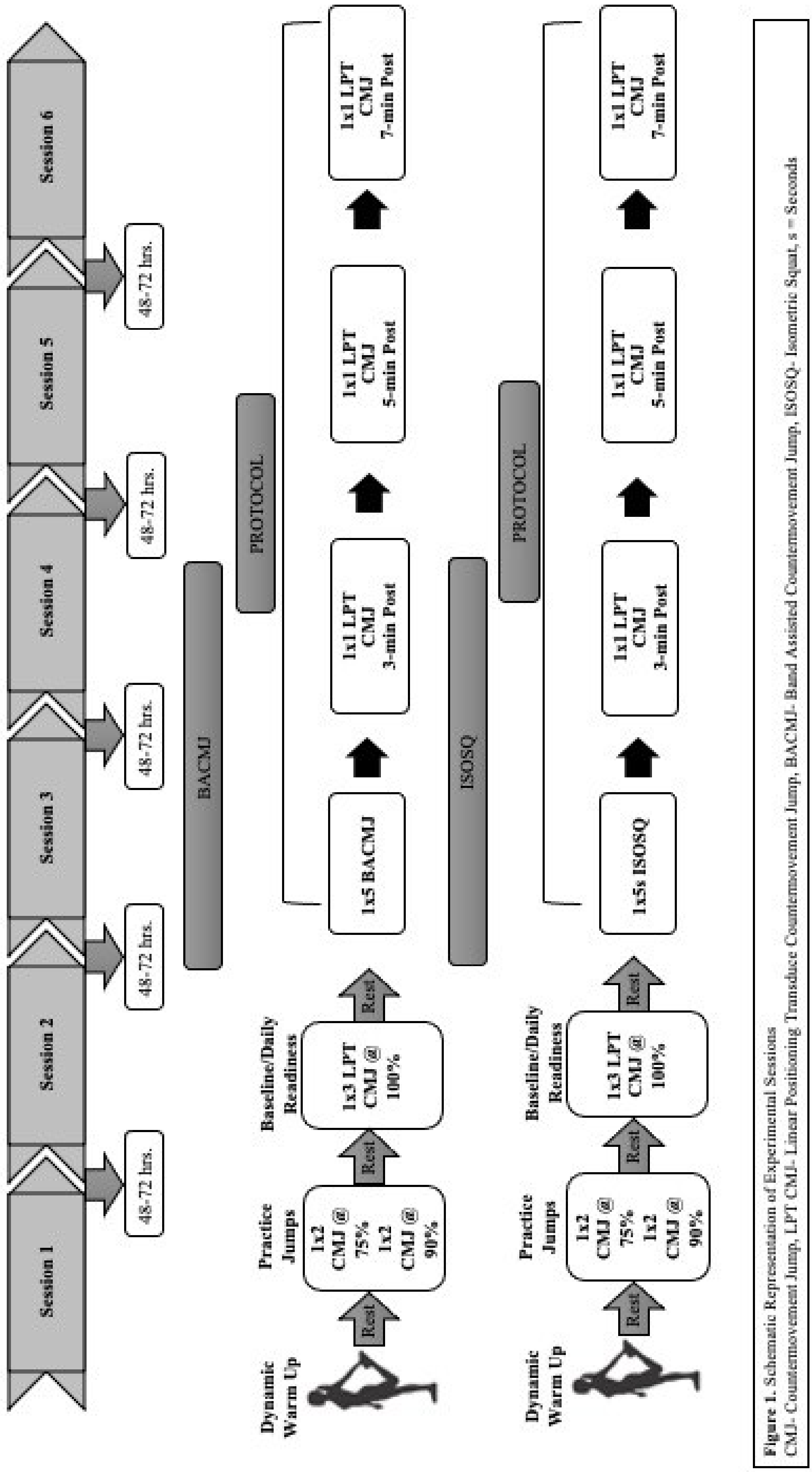

Figure 5. Schematic Representation of Experimental Sessions

5.1.5. Methodologies

5.1.5.a. Subjects

An a priori sample size estimation was performed using G*Power (version 3.1.9.6) with the following design specification considered: $\alpha = 0.05$; $(1-\beta) = .80$; effect size $f = 0.29$; test family = F test, and statistical test = repeated measures ANOVA (within-subject factors). The sample size estimated according to these specifications was sixteen subjects. Therefore, a total of sixteen elite speed skaters 9 males (23.1 ± 2.6 yrs., 179.1± 10.06 cm, 76.91 ± 10.72 kg, relative full back squat 1.92 ± 0.24 kg/kg) and 7 females (24.2 ± 4.7 yrs., 167.7 ± 2.55 cm, 63.58 ± 5.14 kg, relative full back squat 1.62 ± 0.23 kg/kg) of the 2021-2022 United States Long Track and Short Track National Teams participated in this study during the early off-season and late competitive in-season allowing for the limitation of outside stressors and the overall training volume and intensity to be much lower. Inclusion criteria for participation were (a) international and national elite ranking, (b) a minimum of three years of resistance training, (c) previous experience using CMJs, assisted countermovement jumps, and isometric exercises in their training programs, (d) previous experience performing exercises with linear positioning transducers, and no previous lower body injuries or mobility restrictions that would prevent them from participating in the study. All subjects were informed about the potential risks and benefits of the procedures and signed a written informed consent form which was approved by a university ethics board (Appendix #7).

5.1.5.b. Procedures

Following the described standardized dynamic warm up, a baseline CMJ measurement was recorded. All subjects were instructed to perform a quick "dip" by flexing the knees and hips to a self-selected depth and then immediately extending upward to jump vertically from the ground (Figure 6). All subjects were instructed to keep the wooden dowel over their shoulder and their legs straight during the flight phase of the CMJ according to previous study (Tufano et al., 2018). Prior to each baseline CMJ, subjects performed 2 practice jumps (75 and 90% of their perceived effort) followed by 1 set of 3 maximal effort jumps with approximately five seconds of rest to reset prior to beginning the next repetition (Tufano et al., 2018).

All CMJ attempts were performed at maximum effort and were assessed using a Gymaware linear position transducer (LPT) (Gymaware, Kinetic Performance Technology, Canberra, Australia) which was selected due to its previous validation (Harris et al., 2010; Orange et al., 2020; Wadhi et al., 2018). The LPT consists of a Velcro strap at the end of a tether that is wound around a cylinder-like spool which is secured to the shaft of an optical encoder. In the present study, the LPT was placed on the floor next to the subject and was calibrated and “zeroed” while the tether was fully retracted inside the power tool prior to data collection. After calibration, the LPT was attached to the right side of a wooden dowel and positioned across the shoulders of the subject in the high bar back squat position in accordance with previous research (Hojka et al., 2022).

Figure 6. Baseline Jump Protocol

As seen in Figure 6, the subject and the dowel are not completely vertical during the lowering phases of the countermovement; this was accounted for using the Gymaware LPT. The LPT measured the total displacement of its tether in response to changes in the dowel’s position and incorporates an angle sensor that accounts for motion in the horizontal direction during execution of vertical displacement. The LPT software was used to account for the total distance and angle, to provide a resultant vertical displacement (Harris et al., 2010, Wadhi et al., 2018). Jump height (JH) was specifically calculated in the software by considering the distance from the starting (standing) position to the maximum jump height (peak positive displacement).

Furthermore, JH were exported directly from the LPT software, with no additional measurements or calculations performed. The LPT was connected to an iPad (7th generation, Apple Inc., Cupertino, USA) via a Bluetooth connection with the manufacturer’s app installed.

Instantaneous velocity data obtained from the LPT was transmitted via WIFI connection to the online cloud storage before being exported to Microsoft Excel (Microsoft Corporation, Redmond, WA) and prepared for further confidential analysis. To ensure accuracy and verify that all repetitions were adequately performed, all data underwent visual inspection in the online cloud storage before exported.

Experimental Design- Study 1: Predictability of Individualizing Band-Assisted Countermovement Jump PAPE.

Following the described standardized warm up and baseline CMJ measurements, two resistance bands (EliteFTS, Columbus, USA) were attached to a standard pull-up bar overhead at a distance of 1 meter. Subjects were instructed to place their hands on the band and pull their hands down to shoulder-level to reduce bodyweight load by 20% or approximately 14.0 ± 1.7kg in the standing position according to previous studies (Sheppard et al., 2011; Tran et al., 2012; Tran et al., 2011; Tufano et al., 2018). While keeping the hands at shoulder-level, subjects performed one set of five repeated maximal effort BACMJs (repeated countermovement jumps) with the band assisting them upward (Figure 4.). Throughout each repetition and set, subjects were verbally encouraged to "explode off the floor" and "jump as high as possible". (Argus et al., 2011; Tran et al., 2012; Tran et al., 2011).

Experimental Design- Study 2: Predictability of Individualizing Isometric Squat PAPE.

Following the described standardized dynamic warm up and CMJ baseline measurements, subjects positioned themselves on a handcrafted platform designed with a single eye hook in the center of the platform. All subjects connected themselves to the platform via a chained dip belt (Rogue Fitness, Columbus, Ohio, USA) that was anchored to the platform's eye hook. The belt was stressed tested and rated at 29,400lbs in the production factory and no complaints of discomfort were mentioned by subjects during trials. The subjects then assumed a squat position that allowed them to bend their knees to approximately 90 degrees, adopting a torso angle of approximately 45 degrees. To ensure torso and knee angles were consistent throughout the efforts, subjects were allowed to keep their hands extended out at shoulder-level to maintain their balance (Figure 3). Subjects performed a single 5-second maximal effort ISOSQ and were provided verbal encouragement and instructions to "push away from the ground as hard as possible" during the trials, in accordance with previous research (Tillin et al., 2012). The direct outputs measurement of force during the ISOSQ repetition was not collected as force plate technologies were not available during data collection. However, the quality of effort was maintained throughout the entire repetition. After finishing the conditioning activities, subjects rested in a seated position and performed a single maximum-effort CMJ at the 3-, 5-, and 7-minute rest periods in the same manner as the baseline CMJ.

5.1.5.c. Statistical Analysis

While both the BACMJ and ISOSQ projects were combined into one manuscript, both were analyzed independently, as they were originally intended. For both projects, data normality was verified by the Shapiro-Wilk test. Reliability of each baseline jump across all sessions was assessed using a two-way mixed intraclass correlation coefficients (ICC) and coefficients of variation (CV), which were calculated with 95% confidence intervals (CI). All baseline jumps for all sessions exhibited acceptable reliability (ICC $\geq$ 0.75, CV $\leq$ 10%) and very large to near perfect correlation (r= 0.89 – 0.98).

To determine if PAPE successfully occurred, three separate repeated-measures analysis of variance (ANOVA) were concluded across all six experimental sessions for both BACMJ and ISOSQ protocols. Each session included the average of three jumps for baseline and a single jump performance at the different post-PAPE time points. For each protocol, a 1 (condition) x 4 (baseline, 3-min, 5-min, and 7-minute) repeated-measures ANOVA was performed to compare changes in post PAPE JH performance and countermovement depth following conditioning activities (Table 12), which is in line with many previous studies (Cazas et al., 2013; Cazas-Moreno et al., 202; Chatzopoulos et al., 2007; Scott et al., 2018; Seitz 2014). Next, a 1 (condition) x 3 (3-min, 5-min, and 7-minute) repeated-measures ANOVA was performed to compare the relative change (%) in post PAPE JH performance and countermovement depth following the conditioning activities (Table 12), which is also in line with previous research (Chiu et al., 2003; Chiu & Salem 2012; Scott et al., 2018). Lastly, a 1 (condition) x 2 (baseline, and peak) repeated measures ANOVA was performed to compare changes in post PAPE JH performance and countermovement depth regardless of post-PAPE time point (Table 12), which is common when authors state that athletes experience PAPE but at their individualized time point (Cazas-Moreno et al., 202; Mina et al., 2016; Scott et al., 2018). For those analyses, if significant main effects of time were present, a Tukey's post-hoc analysis was used. Hedge's g effect sizes were calculated to measure the magnitude of between-group difference of the post-hoc analysis. These statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) version 28.0.1.1 for Mac (SPSS, Inc., Chicago, IL, USA). Differences were considered significant at a priori alpha level of $p < 0.05$. Males and females were grouped together in all analyses.

Unique to this study and to determine if PAPE could accurately be predicted across multiple sessions (and thereby individualized), a linear-mixed effect model (LMM) analysis was performed across all six experimental sessions. A LMM was selected due to its ability to incorporate random effects, which account for the within-subject variability and repeated measures across multiple experimental sessions in order to identify differences in individual responses. To conduct the analysis, one of the six experimental sessions was randomly chosen to establish the "optimal" time point. Through within-subject and within-day inspection, we identified the post-PAPE rest time point (3-,5-, 7-minutes) that yielded the highest post-PAPE JH for each subject (Figure 7 and Figure 8). This specific rest time point was then designated as the "optimal" time point for each subject. To evaluate the accuracy of our prediction, we compared the JH at this "optimal" time point across the remaining five experimental sessions. Additionally, we compared the JH achieved at the "optimal" time point with the average JH at 3-,5-, and 7-minutes post-PAPE to determine whether the "optimal" time point yielded superior results compared to other randomly chosen (all other) time points. This process was repeated for another random day until all six sessions had been randomly analyzed. All statistical modeling was performed using R statistical language (R Foundation, Vienna, Austria, https://www.R-project.org).

5.2. New Additions to the Existing Literature

As previously stated, the primary goal of this manuscript (Stuart et al. 2024b) was to determine if PAPE (i.e., using a high-velocity and high-force conditioning activity), is repeatable within individuals across multiple experimental sessions. To the best of our knowledge, this is the first study to examine PAPE's consistency across multiple sessions using the same subjects. The study's findings indicated that using traditional statistical methods like ANOVA to identify PAPE across several sessions yields varied results. Specifically, we assessed PAPE's effect on jump height (JH) by comparing the average of three baseline JH measurements with the peak post-PAPE JH at specific rest intervals (3, 5, and 7 minutes). The results showed that PAPE was only evident in one out of six sessions for BACMJ and two out of six sessions for ISOSQ, with Hedges' g effect sizes generally indicating trivial to small differences, except for the 3-minute rest period in session 2 of the ISOSQ protocol. Moreover, the relative change in post-PAPE JH showed a significant main effect for time ($p > 0.05$) in only one of the six sessions. However, when considering the peak post-PAPE JH irrespective of rest time, PAPE was consistently observed across all sessions for both protocols (Table 12).

Table 12. Repeatability of Post-Activation Performance Enhancement Across Multiple Experimental Sessions

	1x4 ANOVA Baseline vs Post Jump Height (cm)		1x3 Relative Percentage Change Baseline vs Post Jump (%)		1x2 ANOVA Baseline vs Peak-Post Jump Height (cm)	
Session 1	**BACMJ *****	**ISOSQ**	**BACMJ**	**ISOSQ**	**BACMJ *****	**ISOSQ ****
Base	0.45 ± 0.05	0.44 ± 0.05			0.45 ± 0.05	0.44 ± 0.05
3-min	0.47 ± 0.07↑	0.45 ± 0.05	104%	100%		
5-min	0.48 ± 0.06↑	0.45 ± 0.06	106%	101%	0.48 ± 0.06	0.45 ± 0.05
7-min	0.47 ± 0.07↑	0.45 ± 0.05	104%	106%		
Session 2	**BACMJ**	**ISOSQ *****	**BACMJ**	**ISOSQ**	**BACMJ *****	**ISOSQ *****
Base	0.45 ± 0.06	0.43 ± 0.05			0.45 ± 0.06	0.43 ± 0.05
3-min	0.46 ± 0.06	0.46 ± 0.05↑	103%	107%		0.46 ± 0.05
5-min	0.47 ± 0.06	0.45 ± 0.06↑	105%	105%		
7-min	0.47 ± 0.07	0.44 ± 0.06	106%	103%	0.47 ± 0.07	
Session 3	**BACMJ**	**ISOSQ**	**BACMJ**	**ISOSQ**	**BACMJ ***	**ISOSQ ****
Base	0.45 ± 0.06	0.44 ± 0.06			0.45 ± 0.06	0.44 ± 0.06
3-min	0.47 ± 0.05	0.46 ± 0.07	103%	104%	0.47 ± 0.05	
5-min	0.46 ± 0.05	0.46 ± 0.06	101%	104%		0.46 ± 0.06
7-min	0.46 ± 0.05	0.45 ± 0.06	103%	102%		
Session 4	**BACMJ**	**ISOSQ ***	**BACMJ**	**ISOSQ**	**BACMJ *****	**ISOSQ *****
Base	0.44 ± 0.05	0.44 ± 0.06			0.44 ± 0.05	0.44 ± 0.06
3-min	0.46 ± 0.06	0.45 ± 0.06	104%	100%	0.46 ± 0.06	
5-min	0.46 ± 0.06	0.46 ± 0.06↑	105%	105%		
7-min	0.45 ± 0.07	0.46 ± 0.07↑	103%	105%		0.46 ± 0.07
Session 5	**BACMJ**	**ISOSQ**	**BACMJ***	**ISOSQ**	**BACMJ *****	**ISOSQ *****
Base	0.45 ± 0.06	0.43 ± 0.06			0.45 ± 0.06	0.44 ± 0.06
3-min	0.46 ± 0.05	0.44 ± 0.06	104%	102%		
5-min	0.48 ± 0.06	0.44 ± 0.05	106%	103%	0.48 ± 0.06	0.44 ± 0.05
7-min	0.46 ± 0.05	0.44 ± 0.06	102%	102%		
Session 6	**BACMJ**	**ISOSQ**	**BACMJ**	**ISOSQ**	**BACMJ *****	**ISOSQ *****
Base	0.46 ± 0.06	0.44 ± 0.07			0.46 ± 0.06	0.44 ± 0.07
3-min	0.46 ± 0.06	0.45 ± 0.05	102%	103%		
5-min	0.46 ± 0.06	0.45 ± 0.05	102%	104%		0.45 ± 0.05
7-min	0.47 ± 0.07	0.44 ± 0.06	102%	101%	0.47 ± 0.07	

Table 12. To determine if PAPE successfully repeatedly occurred, three separate repeated-measures analysis of variance (ANOVA) were concluded across all six experimental sessions for both BACMJ and ISOSQ protocols. 1x4 ANOVA compared changes in post PAPE jump height following conditioning activity, 1x3 ANOVA compared the relative change (%) in post PAPE jump height following conditioning activity, and a 1x2 ANOVA compared changes in post PAPE jump height following conditioning activity regardless of rest time.

* Significant main effect of time at ($p < 0.05$) ** Significant main effect of time at ($p < 0.01$) *** Significant main effect of time at ($p < 0.001$)

↑ Significantly greater than baseline ↑↑ Significantly greater than 3-minutes ↑↑↑ Significantly greater than 5-minutes ↑↑↑↑ Significantly greater than 7-minutes

BAMCJ = Band Assisted Countermovement Jump, ISOSQ = Isometric Squat, cm = centimeter, % = relative percentage change

Additionally, the study aimed to determine whether PAPE could be accurately observed across multiple sessions using "individualized" timing. Linear mixed effect model post hoc analysis revealed that at the within-subject level there was no consistent pattern in JH improvement at specific post-PAPE rest intervals (3, 5, 7 minutes). The variance between the baseline JH average and post-PAPE JH at the "optimal" rest time was not significantly greater than the natural baseline variance. While it was possible to predict post-PAPE JH using an "optimal" rest time for some individuals, there were no statistically significant differences ($p > 0.05$) between the predicted "optimal" and "random" rest times (Table 13).

Table 13. Predicting Enhanced Jump Performance

		Isometric Squat	
Randomly Selected Predictive Day	Individual Data (Applicable Subjects)	Jump Performance Difference (cm)	Predicted vs. Random Rest Time (p-value)
1	7/15 (46%)	0.262	0.161
2	9/15 (60%)	0.361	0.166
3	8/15 (53%)	0.191	0.473
4	6/15 (40%)	-0.024	0.915
5	7/15 (46%)	0.064	0.803
6	7/15 (46%)	0.033	0.880
		Band Assisted Countermovement Jump	
Randomly Selected Predictive Day	Individual Data (Applicable Subjects)	Jump Performance Difference (cm)	Predicted vs. Random Rest Time (p-value)
1	5/12 (41%)	-0.112	0.396
2	6/12 (50%)	0.062	0.664
3	4/12 (33%)	-0.176	0.221
4	7/12 (58%)	-0.315	0.140
5	5/12 (41%)	-0.154	0.375
6	7/12 (58%)	-0.006	0.972

Table 13. A linear mixed effects model was utilized to predict individualized PAPE timing across all six experimental sessions. From these sessions, one was randomly selected to establish the "optimal" time point by observing changes in jump height (JH) within the subject and across the day at various post-PAPE rest intervals (3-, 5-, and 7-minutes). The accuracy of PAPE timing prediction was evaluated by comparing the JH at the "optimal" time point across the remaining five sessions. This "optimal" time point JH was also compared with the average JH from three post-PAPE jumps within the same session to determine its superiority over other randomly chosen time points. This process was repeated for additional random days until all six sessions were included in the analysis.

cm= centimeters, JH = Jump Height

5.2.1. ANOVA Statistical Analysis

Traditionally, PAPE studies have employed repeated measures ANOVA to examine group-level differences and identify when the group average PAPE performance exceeds baseline (Cazas et al., 2013; Cazas-Moreno 2021; Chatzopoulos et al., 2007; Scott et al., 2018; Seitz et al., 2014). Previous research has reported improved jump performance within specific rest periods, typically 2 to 5 minutes for high-velocity (BACMJ) (Cazas et al., 2013; Cazas-Moreno 2021; Markovic & Jaric 2007; Tufano et al., 2018b) and 1 to 5 minutes for high-force (ISOSQ) PAPE (French & Kraemer 2003; Gossen & Sale 2000; Gullich & Schmidtbleicher 1996). Our findings generally align with these time ranges, though multi-day analysis indicated that performance improvements might also occur with a 7-minute rest period, suggesting longer rest times might be effective for both PAPE protocols. However, the multi-day analysis revealed significant main effects for time in only a few sessions, with mean differences in JH not consistently aligning with specific rest intervals or producing significant results ($p > 0.05$) (Table 12). Furthermore, results showed that while countermovement depth significantly increased at 5- and 7-min post-PAPE during session three, these changes did not lead to meaningful improvements in JH, with effect sizes remaining trivial to small. This emphasizes the challenges in determining the conditions under which PAPE effects consistently occur across different sessions and time points, suggesting that the enhanced jump performance response to PAPE may not be definitive or repeatable across multiple experimental sessions.

In cases where average group performance across different rest times did not show a significant main effect for time ($p < 0.05$), researchers have used baseline versus peak-post performance analysis (1x2 ANOVA) to determine if potentiation occurred. This method often concludes that PAPE can occur at an individualized time point (Cazas-Moreno 2021; Mina et al., 2016; Scott et al., 2018). Our study produced similar results, where identifying PAPE through a baseline versus peak-post analysis yielded significant results ($p < 0.005$) across all sessions for both protocols (Table 12). These findings support the use of peak-post PAPE performance analysis, irrespective of specific rest times, as a valid method for assessing the effectiveness of conditioning activities in enhancing jump performance (Cazas-Moreno 2021; Chatzopoulos et al., 2007; French & Kraemer 2003; Gossen & Sale 2000; Gullich & Schmidtbleicher 1996).

Previous studies have acknowledged the limitations of these analyses and attempted to investigate PAPE at the individual level. To "individualize" PAPE responses, studies have examined the relative change in performance, known as percent potentiation (Chiu et al., 2003;

Chiu et al., 2012), maximum potentiation response (Scott et al., 2018), or percentage improvement (Seitz et al., 2014). This approach can help identify enhanced performance, especially when considering factors like training age (Chiu et al., 2003) and relative strength (Chiu et al., 2012; Seitz et al., 2014). In our study, a significant main effect for time was observed in only one of six sessions when examining relative changes in JH following BACMJ and ISOSQ PAPE. However, post-hoc analysis did not reveal significant differences between rest times, highlighting the lack of repeatability (Table 12). Unlike previous studies, all subjects in our study were elite-level speed skaters with significant training age and relative strength levels, suggesting that these factors may not significantly influence PAPE responses.

Possible mechanisms for JH improvement, regardless of time, in both BACMJ and ISOSQ conditions include higher myosin light chain phosphorylation (Blazevich & Babault 2019; Boullosa et al., 2018; Docherty & Hodgson 2007; Tillin & Bishop 2009), increased central drive activation (Docherty & Hodgson 2007; Prieske et al., 2020; Tillin & Bishop 2009), rapid force production (Docherty & Hodgson 2007), increased neural activity following acute neuromuscular enhancement from an over-speed movement (Cazas et al., 2013), and changes in muscle pennation angle (Tillin & Bishop 2009)). From a practical perspective, our study highlights the challenges of implementing PAPE consistently, as predicting performance enhancements over multiple days or at specific rest times remains difficult. This unpredictability complicates scheduling in strength and conditioning settings.

5.2.2. Linear Mixed Effect Methods Analysis

A secondary objective was to explore the individualization of PAPE timing by identifying a predicted "optimal" time point post-hoc, based on data collected across multiple sessions. Prior research (Scott et al., 2018) suggested that individualized intra-complex recovery intervals (ICRIs) could enhance countermovement jump (CMJ) performance. However, the consistency of this effect across multiple sessions was not previously investigated. In practice, if PAPE could be individualized, we would expect (a) consistent maximum JH at the same time for each individual on different days, (b) greater variance in JH at 3-, 5-, and 7-minutes post-PAPE than baseline variance, and (c) higher JH at the "optimal" rest time compared to a "random" time.

Our study found that post-PAPE JH performance did not show a consistent pattern at specific rest times across multiple sessions for both BACMJ (Figure 7) and ISOSQ (Figure 8) conditions. Additionally, the coefficient of variance for JH at 3-, 5-, and 7-minute post-PAPE was comparable to the baseline variance, indicating no significant increase in variance post-

PAPE. Session-to-session coefficient of variance also showed minimal differences between post-PAPE and baseline performances, suggesting that PAPE may not consistently enhance performance across multiple sessions.

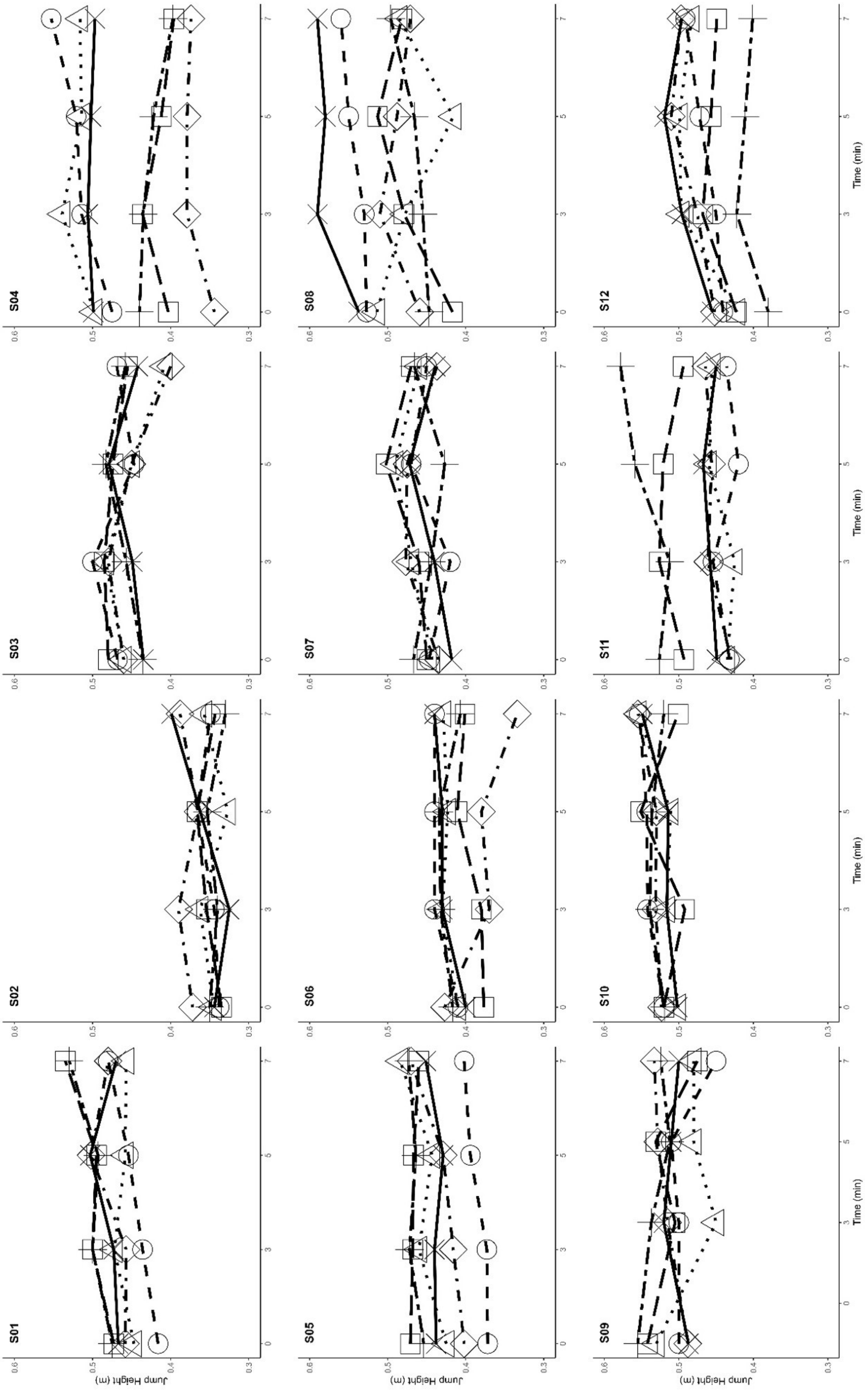

Figure 7. Within-Subject and within-day inspection of Band Assisted Countermovement Jump post-PAPE Jump Height

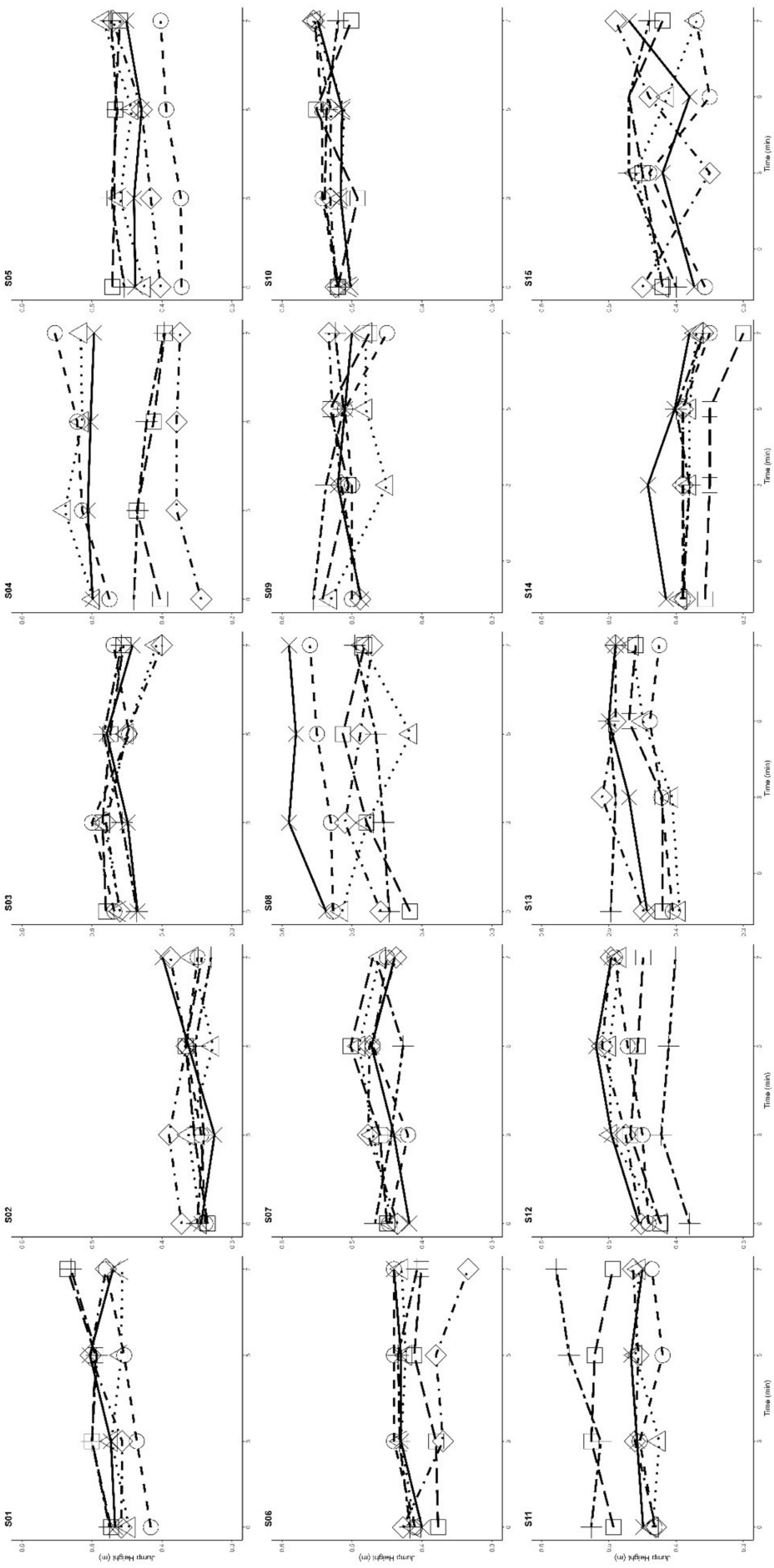

Figure 8. Within-Subject and within-day inspection of Isometric Squat post-PAPE Jump Height

If there were a time effect on PAPE as previous literature has presented, we would expect greater variance between the baseline JH and JH at 3-, 5-, and 7-minutes post-PAPE. The linear mixed-effects model (Equation 4) indicated that PAPE was only predicted in a minority of subjects, and the "optimal" rest time did not significantly outperform the "random" time point (Table 12). These findings suggest that while PAPE can be identified, it does not follow a consistent or repeatable pattern across multiple sessions, making it challenging to individualize rest times for PAPE effectively.

Equation 4. Linear Mixed Effect Model Post-hoc Individualized Optimal Timing

$$JHijkm = \beta 0 + \beta 1 Time\ Pointikm + \beta 2 Sessionjm + \beta 3 (Time\ Point \times Session) ijkm + u0j + u1j Time\ Pointikm + eijkm \quad (4)$$

The result of the present study suggests that, on average across all subjects, jump performance at the 3-, 5-, and 7-minutes post-PAPE did not show significant variance compared to baseline performance. Suggesting that a general warm up (GWU) may provide similar benefits to PAPE and that it may not be beneficial to individualize the rest time for PAPE. Furthermore, when examining the session-to-session coefficient of variance, the analysis revealed that, on average, there were minimal differences in performance between post-PAPE and baseline across all six sessions for both BACMJ and ISOSQ suggesting that the variance within a single session may not lead to enhanced jump performance in response to implementing PAPE thus it may not be definitive or repeatable across multiple training sessions.

From a practical application perspective, if there was a time effect on PAPE, we would have anticipated a larger variance between the average of three baseline jumps and the jump height at 3-,5-, and 7-minutes post-PAPE. Additionally, when using a linear-mixed effects model, PAPE was successfully predicted in only a minority of subjects for both protocols. However, the performance at the "optimal" rest time did not yield significantly better results compared to the "random" time point. If individualizing PAPE timing were indeed possible, we would have observed clear evidence that the individual's "optimal" time point produced superior results compared to "random" time point. These results support the idea that PAPE can be identified, but there is no consistent or repeatable pattern of performance enhancement over multiple training sessions. Therefore, it may not be beneficial to “individualize” the rest time for PAPE.

5.2.3. Additional Considerations

Some might argue that the restricted rest times (3-, 5-, and 7-minutes) used in this study limited the ability to identify a PAPE response. However, our findings suggest that PAPE responses were not individualized or consistent even within these intervals. Future studies might consider longer rest periods to validate this hypothesis. It is also important to note that the subjects were experienced with the exercises used (BACMJ, CMJ, and ISOSQ), which minimized novice effects and allowed for higher data quality. The study was conducted during a period where strength training was the primary focus, reducing the impact of external stressors on the results.

Potential limitations include the possibility that including the "optimal" time point in the post-PAPE JH average calculation could inflate results. Future research should consider additional time points or exclude the optimal time from the average calculation.

In conclusion, both conditioning activities effectively enhanced jump performance within the tested rest times. However, different ANOVA analysis methods yielded varying interpretations across sessions, introducing unpredictability when applying PAPE in practice. Our study emphasizes that PAPE is not consistently repeatable across multiple sessions, challenging the idea of "individualizing" PAPE rest times.

5.3. Practical Application

The main findings of the present study highlight the difficulties of achieving consistent PAPE effects within individuals over time. Of importance, jump height varied across multiple sessions, making it difficult to observe repeatable individual responses over time. Moreover, inconsistencies were seen when comparing specific post-PAPE rest time points between sessions. Lastly, using an “optimal” rest time did not lead to consistent improvements in jump height, as the variance in jump height at baseline was similar to post-PAPE, raises doubts about the effectiveness of personalizing PAPE strategies. These findings introduce critical considerations for strength and conditioning professionals regarding the practical application of PAPE strategies. The present study demonstrates the challenges of achieving repeatable PAPE responses within individuals over time. These results highlight that the practical application of PAPE may be limited due to the inconsistency of performance enhancement. Strength and conditioning coaches should consider using general warm-up routines instead of trying to individualize PAPE strategies in hopes of enhancing jump height performance.

6. Overall Conclusion of Doctoral Thesis

6.1. Synthesis of Findings

This dissertation explored the multifaceted demands of competitive speed skating by examining the biomechanical, physiological, and training considerations integral to enhancing performance. Through three studies, novel insight into performance profiling, training methodologies, and the variability of training-induced adaptations were presented, providing a comprehensive understanding of speed skating's performance determinants.

Chapter 3 identified critical gaps in existing literature regarding the physiological and biomechanical demands of speed skating. This study emphasized the importance of integrating sport-specific assessments, such as split-time analysis and force-power-velocity profiling, into talent identification and training programs. These findings laid the foundation for more precise and individualized approaches to athlete development.

Chapter 4 provided an in-depth analysis of the reliability of acceleration, velocity, and split-time measurements during the 100-meter start in competitive speed skating. The results demonstrated that key metrics, such as mean velocity at 20–70 meters and mean acceleration at 0–20 meters, were reliable and significantly correlated with overall performance. These findings underscore the critical role of phase-specific monitoring in identifying performance strengths and limitations, offering a framework for refining training interventions.

Chapter 5 investigated the consistency of postactivation performance enhancement (PAPE) effects on countermovement jump (CMJ) performance following high-velocity (BACMJ) and high-force (ISOSQ) conditioning activities across multiple sessions. The study highlighted substantial interindividual variability in PAPE responses, raising questions about the practicality of individualizing PAPE timing in speed skating. While both BACMJ and ISOSQ elicited performance improvements, their inconsistent effects across sessions

Together, these studies provided a cohesive framework for understanding the complex interaction of physiological and biomechanical factors influencing speed skating performance. They also highlight the need for tailored, evidence-based approaches to assessment and training.

6.2. Practical Implications

The findings from this dissertation hold significant implications for speed skating performance and training. Coaches and practitioners can utilize the reliable metrics identified in Chapter 4 to design targeted interventions. For instance, focusing on maximal force production during the 0–20 meter phase can enhance early acceleration, while improving velocity maintenance during the 20–70 meter phase can optimize overall sprint performance (de Koning et al., 1993; Zukowski et al., 2023).

Additionally, the studies from this dissertation emphasize the importance of aligning off-ice strength and conditioning programs with on-ice technical training. The use of phase-specific metrics can guide the selection of training modalities, such as plyometrics, resistance exercises, and sprint drills, to address specific performance gaps (Lafontaine, 2007; Haug et al., 2017; Silva et al., 2014).

Furthermore, the findings support the adoption of field-based assessments, such as split-time analysis and force-velocity profiling, as practical tools for monitoring athlete progress. These methods provide actionable data that can inform training adjustments and long-term development strategies, particularly for sprint distances like 500 meters (Weakley et al., 2023; Clark et al., 2017).

Lastly, these findings show that reliable and specific metrics, as demonstrated in Chapter 4, can aid in identifying athletes with the potential for success in speed skating. Incorporating these assessments into national and international training programs can streamline talent development pathways (Stuart et al., 2025).

6.3. Limitations

While this dissertation provides valuable contributions, several limitations warrant further investigation. The studies focus on elite speed skaters, which may limit the applicability of findings to other population or competition levels. Future research should examine these metrics across a broader range of skill levels and age groups (Van Ingen Schenau, 1987; Upjohn et al., 2008). The inconsistent effects of PAPE highlight the need for additional research into individual response patterns and the mechanisms underlying performance variability within a larger cohort. External conditions, such as ice quality and equipment design, were not addressed in this research but remain critical for improving performance. Future studies should consider these variables to provide a more holistic understanding of speed skating demands.

6.4. Future Research Direction Interests

The findings from this dissertation provide a foundation for future investigation into speed skating performance and training methodologies. However, advancing this knowledge requires targeted research to address existing gaps and emerging questions. The following areas of interest outline critical pathways for future exploration:

6.4.1. Training Load and Response to Load in elite speed skaters.

Speed skating, like other time-trial Olympic sports such as track and field, swimming, and cycling, involves a complex interplay of training modalities that demand a nuanced understanding of load distribution and athlete response. Building on prior research of Orie et al., 2014, future research should aim to a.) investigate the distribution of training load across external (e.g., power output, distance covered, etc.) and internal (e.g., heart rate, session rating of perceived exertion, etc.) metrics during on-ice, off-ice, and strength training sessions, b.) examine the dose-response relationship of different training sessions and modalities, particularly when multiple types of session are conducted in a single training day. Identifying how session type, sequence, and timing influence performance and recovery could inform the best practices for improving performance and health, c.) assess the training effects on physiological adaptations, particularly when integrating strength, technical, and on-ice training into a cohesive periodized plan. This research could provide valuable insights into how elite speed skaters and coaches can manage training demands effectively while enhancing performance and mitigation injury risk.

6.4.2. 100-meter acceleration and 500-meter performance

Building on the foundation of Chapter 5 (Stuart et al., 2025), the 100-meter acceleration phase is pivotal for competitive success in speed skating sprint events, particularly for the 500-meter races. While this dissertation has addressed the reliability of acceleration and velocity metrics, future studies should focus on a.) evaluate the between session reliability of these metrics and their correlations with 500-meter race outcomes, b.) investigate the biomechanical and physiological demands at critical race phases, such as the corner apex (150-meter mark) and corner exit (200-meter mark). This would provide insights into the strategies and strength requirements necessary to sustain or enhance velocity during cornering, c.) identifying how strength training, technical adjustments, and tactical decisions influence performance through these critical race segments. Such research would deepen the understanding of phase-specific performance factors and offer actionable guidance for athletes and coaches.

6.4.3. Braking and Propulsive Phase of Countermovement Jump and 100-meter Acceleration Profiling.

The countermovement jump is widely used in sport science as an assessment of neuromuscular performance and monitoring training responses (e.g., fatigue) (McMahon et al. 2018). While its application in speed skating has been explored, further research should evaluate a.) investigating the force-time characteristics of the braking and propulsion phase of the CMJ and their relationship with 100-meter and 500-meter sprint times. The braking phase reflects an athlete's ability to decelerate and control eccentric forces, while the propulsion phase highlights force production capacity during concentric movement, b.) explore how these phases relate to on-ice performance metrics, such as acceleration and velocity, to determine the CMJ's predictive value for speed skating sprint outcomes, c.) identify training interventions that improve CMJ performance and translate these improvements into enhanced on-ice sprint performance. Given the biomechanical parallels between CMJ dynamics and the demands of speed skating, understanding these relationships could improve athlete monitoring and development.

6.5. Final Remarks

This dissertation significantly enhances the understanding of key performance determinants in speed skating by addressing key gaps in assessments and training methodologies. The findings underscore the importance of integrating reliable, phase-specific metrics into training frameworks, facilitating targeted interventions that align with the sport's unique biomechanical and physiological demands. Furthermore, the insights into PAPE variability provide a foundation for refining strength and conditioning strategies, ensuring that skaters can maximize their explosive potential in competition.

By bridging the gap between research and practice, this work equips coaches and practitioners with the tools to enhance athlete development, improve training outcomes, and elevate competitive speed skating performance. Future research should continue to build on these findings, exploring innovative methods to further individualize and improve training methodologies in this dynamic and demanding sport.

7. References

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8. List of attachments

Appendix 1. Confirmation of manuscript submissions and status.

Appendix 2. Accepted abstract at the National Strength and Conditioning Association Annual Conference, Las Vegas, NV USA, July 2023

Appendix 3. Accepted abstracts at the National Strength and Conditioning Association Annual Conference, New Orleans, LA, USA, July 2022

Appendix 4. Accepted abstract Scientia Movens, Prague, Czech Republic, 2021 (Online).

Appendix 5. Accepted chapter contribution to the NSCA Developing Speed 2nd Edition

Appendix 6. The approved form of facility permission letter by the US Speedskating High Performance Director

Appendix 7. The approved form by the Institutional Review Board of the Health and Human Performance Department at University of Chicago Concordia, USA.

Appendix 1. Confirmation of manuscript submissions and status.

Strength Training and Development in Competitive Speed Skating

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ABSTRACT

Speed skating is a time trial–based sport that requires skill, strength, power, and capacity. The unique demands of the sport require a thorough need analysis to better understand the physical requirements, potential injuries, and periodization to successfully prepare athletes. This article will focus on the overall development of the short-distance to middle-distance speed skater to provide coaches, athletes, and strength and conditioning professionals an understanding of the biomechanical, physiological, and energy system demands of the sport and to identify common injuries that are sustained from repeated efforts.

INTRODUCTION

Speed skating is a unique sport that originated in the Netherlands in the 13th century. In 1924, the sport first appeared in the Chamonix Olympic Winter games (24). There are several specialties within the sport of speed skating including long track, short track, and marathon. This article will focus on long-track speed skating and more specifically the short-distance (500 and 1,000 m) and middle-distance (1,500 m) skater. Long-track speed skating is a time trial–based sport that requires the athlete to compete against a clock rather than each other. Although the skaters compete against a clock, the trials are run in pairs, so there is some level of human competition throughout the race. The distances that are covered can be classified into 3 different events: sprint (500 and 1,000 m), middle distance (1,500 m), and long distance (3,000, 5,000, and 10,000 m) (24). World Cup circuits are held seasonally in North America, Asia, and Europe and take up most of the fall and winter calendar with the end of the season occurring in the early weeks of March. Each competition is important because athletes are racing each circuit for a chance to gain World Cup points and medals.

Some aspects of speed skating are similar to other sports both from the specific environment and surface to energy system development. Short-track speed skating is a different discipline in the sport; however, it shares the same distance covered, biomechanical and physiological aspects, and similar training as long track. Other sports, such as ice hockey, also share similar aspects of biomechanics, energy system development, and potential injuries to speed skating. In 2015, Konings et al. (25) reviewed a large amount of literature on the sport of speed skating. The authors reviewed publications from 1971 until 2014 to investigate anthropometrical, technical, physiological, tactical, and psychological characteristics of speed skaters. From the authors' findings we can have several key performance takeaways such as elite speed skaters skate with small knee and trunk angles; there is still a desire to find the optimal balance between pacing strategies among elite-level skaters, regardless of sex; losing 1 kilogram of fat can improve performance in the 500 m by 0.12 s; and that the psychological practice of self-regulation needs to be further investigated in elite speed skaters. These findings were supported by Hofman et al. (23) whose most recent publication investigating Wingate testing as a strong predictor of 1,500 m performance. To date, outside of this review and several other studies, there are not many research topics in the realm of strength and power training that have included the sport of speed skating.

With the limited amount of literature on the sport, and limited exposure of the sport in Western countries such as the United States, training and coaching the speed skating athlete can be rather challenging. The lack of

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KEY WORDS:
speed skating; periodization; injury prevention; strength; power; energy system development

From: **Journal of Strength and Conditioning Research** em@editorialmanager.com
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To: Andrew Stuart astuart33@gmail.com

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Dec 30, 2024

RE: JSCR-08-20644R2, entitled "Investigating the consistency in countermovement jump performance following high velocity and high force PAPE: a multi-day analysis."

Dear Dr. Stuart,

I am pleased to inform you of the official acceptance of your manuscript, JSCR-08-20644R2, entitled "Investigating the consistency in countermovement jump performance following high velocity and high force PAPE: a multi-day analysis." for publication in the Journal of Strength and Conditioning Research. Congratulations to you and your co-authors in meeting the very high standard of quality that is required for publication in this Journal.

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Journal of Strength and Conditioning Research

MEASUREMENT IN PHYSICAL EDUCATION AND EXERCISE SCIENCE
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Accelerating Performance: Reliability of Phase-Specific Measurements in Elite Speed Skaters' 100-Meter Starts

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ABSTRACT

This study examined within-session reliability and minimal detectable change (MDC) in mean split time, velocity, and acceleration across 100-meter start phases (0–20, 20–50, 50–70, 70–100 m) in elite speed skaters. Nineteen skaters (10 females, 9 males) completed two trials on the same day on a 400-meter indoor ice track under standardized conditions, with split times recorded every 10-meters using an automated timing system. Results showed acceptable reliability for mean split time (ICC = 0.84, CV = 7.5%, MDC = 0.00–0.15 s) and velocity (ICC = 0.79, CV = 9.2%, MDC = 0.21–1.09 m·s^{-1}). Mean acceleration showed moderate reliability (ICC = 0.70, CV = 12.4%) and higher variability over greater distances (70–100 m). These findings support using the 100-meter acceleration profile to assess key performance elements (initial start and sustained acceleration), emphasizing the need to tailor training and assessments to specific race phases.

KEYWORDS
Speed skating; sprinting; assessments; minimal detectable change

Introduction

Long-track speed skating is a time trial sport that requires the development of various physical qualities such as strength, power, and speed. Skaters compete in sprint (500 and 1000-meters), middle (1500-meter), and long-distance events (3000-,5000-, and 10,000-meter), where success, particularly in the 500-meter and 1000-meter events, is influenced by the ability to generate high horizontal velocities with large force outputs (de Koning & van Ingen Schenau, 2000; Edwards et al., 2021; Konings et al., 2014). Research highlights the importance of initial 100-meter performance in determining final competition placement (de Koning et al., 1989). However, while the start phase (0–50 meters) has been examined (Song et al., 2018; Zukowski et al., 2023), no studies have thoroughly investigated the entire 100-meter start sequence. Examining the full 100-meters provides critical insights into the transition from the explosive start to sustained acceleration, which is essential in the sprinting events. Understanding this progression can inform training strategies, particularly for events like the 500-meter, where velocity after the initial acceleration phase is crucial for competition success (de Koning et al., 1989).

To this end, it is essential to examine the biomechanics of the start in greater detail. The speed skating start is comparable to an off-ice track start, with skaters exerting high muscular force to accelerate (de Koning & van Ingen Schenau, 2000; Houdijk et al., 2003; Konings et al., 2014; Stuart & Cochrane-Snyman, 2022). This initial push-off involves extensor muscles like the gluteus maximus and vastus medialis, which generate the necessary force for forward acceleration (de Boer et al., 1987; Houdijk et al., 2000). In addition to muscle engagement, an important factor in the initial start is higher knee extension velocity, which has been found to correlate with improved acceleration performance (Buckeridge et al., 2015; Lafontaine, 2007; Robbins et al., 2018). The start phase transitions from shorter, faster strides to longer, gliding strides at approximately 50-meters, where skaters typically reach peak acceleration (de Koning et al., 1989, 1993).

Furthermore, the differences in push-off mechanics, stride length, and ground contact times between the start and later sprint phases also play a significant role in overall performance (de Koning & van Ingen Schenau, 2000; Stuart & Cochrane-Snyman, 2022). Studies in both track sprinting (Healy et al., 2022),

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/1091367X.2025.2451615

Appendix 2. Accepted abstract at the National Strength and Conditioning Association Annual Conference, Las Vegas, NV USA, July 2023

CARROLL UNIVERSITY

SPORT PERFORMANCE INSTITUTE

RELATIONSHIPS BETWEEN COUNTERMOVEMENT JUMP FORCE-TIME CHARACTERISTICS AND 500-METER SPRINT TIME IN SPEED SKATERS

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CONCORDIA UNIVERSITY CHICAGO

Introduction

The 500-m event is the shortest distance of the long-track speed skating disciplines, whereby two skaters per heat compete on a 400-m oval. Like off-ice sprinting competitions, speed skating results are based upon completing a specific distance in the shortest possible duration. While off-ice training may benefit speed skating initial sprint performance (1,4), less is known about how the force-time characteristics of speed skaters relates to their sprint performance. The countermovement jump (CMJ) is one of the most common performance assessments within athlete testing batteries. McMahon and colleagues (3) indicated that the braking and propulsion phases of the CMJ are useful tools to understand how an athlete produces vertical force to stop their downward momentum before propelling themselves vertically. Given the need to generate large magnitudes of force within short durations to accelerate during a 500-m on-ice sprint (2), it would seem logical that CMJ braking and propulsion force-time characteristics would relate to 500-m sprint time of speed skaters. Therefore, the purpose of the current study was to examine the relationships between CMJ braking and propulsion force-time characteristics and 500-m sprint time in national and international level speed skaters. It was hypothesized that CMJ force-time characteristics would relate to on-ice 500-m sprint time in national and international level speed skaters.

Methods

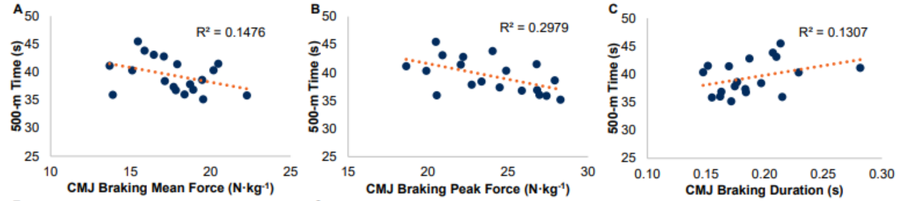
- 9 male (21.0 ± 2.6 years, 77.9 ± 10.1 kg, 179.9 ± 8.8 cm) and 10 female (20.8 ± 4.4 years, 64.9 ± 5.1 kg, 167.9 ± 3.6) 500-m national and international level speed skaters performed two CMJ trials one week before the 2022 Olympic Trials.
- Participants performed self-selected dryland warm-up prior to completing warm-up jump trials at 50 and 75% of their perceived maximum effort.
- Two maximal CMJ trials were performed with the subjects' arms akimbo on dual Pasco force plates (PASCO Scientific, Roseville, CA).
- Force-time data were exported to and analyzed using a custom spreadsheet (Microsoft, Redmond, WA).
  - Variables included CMJ height, braking mean force, peak force, and duration and propulsion mean force, peak force, and duration.
- 500-m times were obtained from the Olympic Trials one week after CMJ assessments.
- The average performance between CMJ trials was used to examine the relationships of each variable and the 500-m sprint time.
- Pearson correlation coefficients (r) and coefficients of determination (R^2) were used to examine the relationships between CMJ force-time characteristics and 500-m sprint time.

Results

Table 1. Countermovement jump force-time characteristics.

	JH (m)	BMF (N·kg⁻¹)	BPF (N·kg⁻¹)	BDur (s)	PMF (N·kg⁻¹)	PPF (N·kg⁻¹)	PDur (s)	500-m (s)
Mean	0.38	17.7	23.9	0.19	19.2	24.3	0.30	39.42
±	±	±	±	±	±	±	±	±
SD	0.08	2.3	3.0	0.03	1.8	2.6	0.03	3.08
r	0.885**	-0.384	-0.546*	0.361	0.763**	0.683**	0.533*	-

Note: r values relate to 500-meter times. JH = jump height; BMF = braking mean force; BPF braking peak force; BDur = braking duration; PMF = propulsion mean force; PPF = propulsion peak force; PDur = propulsion duration; * = significant at 0.05 level; ** = significant at 0.01 level



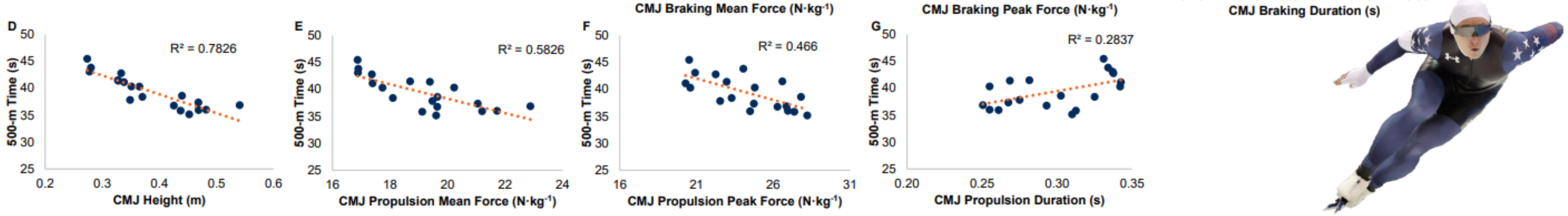


Figure 1. Relationships between 500-m sprint time and countermovement jump (CMJ) braking mean force (A), braking peak force (B), braking duration (C), height (D), propulsion mean force (E), propulsion peak force (F), and propulsion duration (G).

Conclusions

- Very large relationships existed between CMJ height and propulsion mean force and the 500-m sprint times in national and international level speed skaters.
- A large portion (78.3%) of the 500-m time variance was explained by CMJ height indicating the potential to use this variable to monitor a speed skater's performance.
- It is also important to develop the propulsive strength characteristics of speed skaters given that 58.2% of the 500-m time variance was explained by propulsion mean force.
- CMJ braking characteristics do not appear to be effective monitoring variables for speed skaters due to only small portions of 500-m sprint time variance being explained.

Practical Applications

- Strength and conditioning practitioners may consider using CMJ height as a monitoring variable with short distance speed skaters.
- It is evident that maximizing a speed skater's propulsive strength characteristics (i.e., peak force and rapid force production) may positively impact speed skating sprint performance.
- Practitioners should implement dryland and resistance training strategies to benefit these characteristics.

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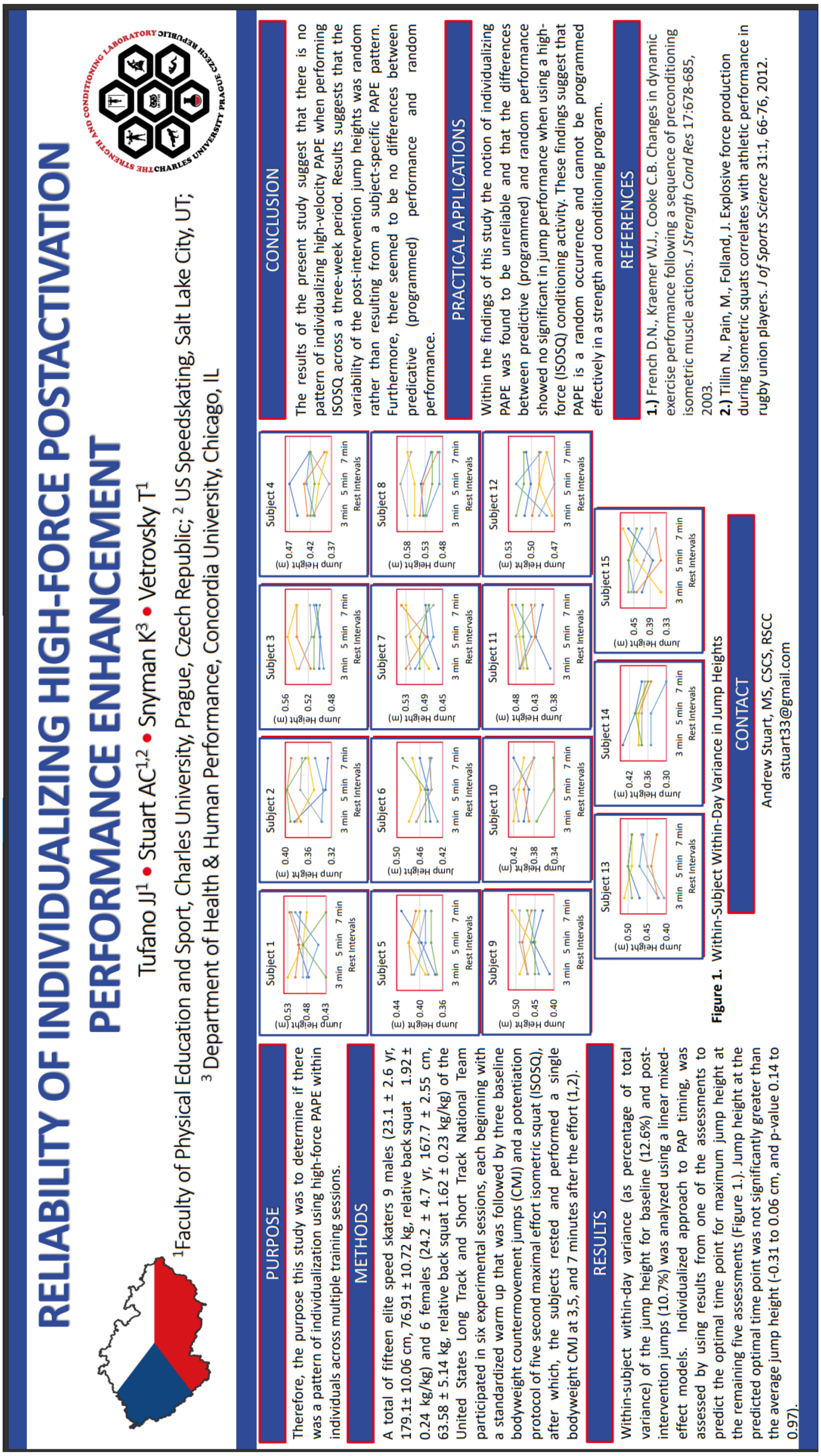
NSCA National Strength and Conditioning Association National Conference NSCA
Las Vegas, NV July 12 – 15, 2023

Appendix 3. Accepted abstract at the National Strength and Conditioning Association Annual Conference, New Orleans, LA, USA, July 2022



RELIABILITY OF INDIVIDUALIZING HIGH-VELOCITY POSTACTIVATION PERFORMANCE ENHANCEMENT

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PURPOSE

The purpose of this study was to determine if there was a pattern of individualization using high-velocity PAPE within individuals across multiple training sessions.

METHODS

A total of twelve elite speed skaters 8 males (23.1 ± 2.6 yr, 179.1± 10.06 cm, 76.91 ± 10.72 kg, relative back squat 1.92 ± 0.24 kg/kg) and 4 females (24.2 ± 4.7 yr, 167.7 ± 2.55 cm, 63.58 ± 5.14 kg, relative back squat 1.62 ± 0.23 kg/kg) of the United States Long Track and Short Track National Team participated in six experimental sessions, each beginning with a standardized warm up that was followed by three baseline bodyweight countermovement jumps (CMJ) and a potentiation protocol of five repeated band assisted countermovement jumps (BACMJ) (Figure 1.), after which, the subjects rested and performed a single bodyweight CMJ at 3,5, and 7 minutes after the effort (1,2).

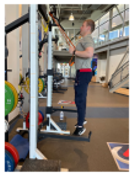

Figure 1. Band Assisted Countermovement Jump

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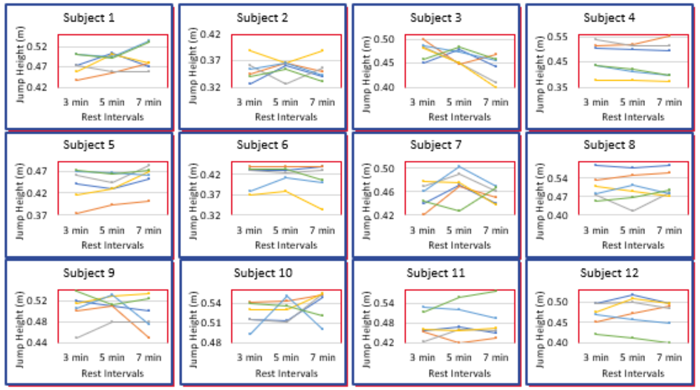

Figure 2. Within-Subject Within-Day Variance in Jump Heights

RESULTS

Within-subject within-day variance (as percentage of total variance) of the jump height for baseline (9.2%) and post-intervention jumps (10.9%) was analyzed using a linear mixed-effect models. Individualized approach to PAPE timing, was assessed by using results from one of the assessments to predict the optimal time point for maximum jump height at the remaining five assessments (Figure 2.). Jump height at the predicted optimal time point was not significantly greater than the average jump height (-0.02 to 0.36 cm, and p-value 0.91 to 0.16).

CONCLUSION

The results of the present study suggest that there is no pattern of individualizing high-velocity PAPE when performing BACMJ across a three-week period. Results suggests that the variability of the post-intervention jump heights was random rather than resulting from a subject-specific PAPE pattern. Furthermore, there seemed to be no differences between predicative (programmed) performance and random performance.

PRACTICAL APPLICATIONS

Within the findings of this study the notion of individualizing PAPE was found to be unreliable and that the differences between predictive (programmed) and random performance showed no significant in jump performance when using a high-velocity (BACMJ) conditioning activity. Strength and conditioning practitioners should use caution when trying to use the concept of individualizing PAPE.

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RELIABILITY AND MINIMAL DETECTABLE CHANGE OF 100-METER SPEED SKATING ACCELERATION PROFILING

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PURPOSE

The purpose of this study was to investigate the inter-day reliability and minimal detectable change of on-ice 100-meter acceleration sprint times.

METHODS

A total of 10 female (168 cm ± 3.4 cm, 65.1 kg ± 4.8 kg) and 9 male (180.5 cm ± 9.2 cm, 78.6 kg ± 10.5 kg) 500-meter junior and senior level speed skaters of various international and national experience performed 2 trials of 100-meter accelerations one week prior to the 2022 Olympic Trials. Timing gates were set at every 10-m interval of the 100-meter front stretch of the 400-m oval with the lasers set to 41 centimeters above the surface of the ice (Figure 1.). All subjects performed a self-selected dryland and on-ice warm up. Subjects then performed two 100-m maximal sprint skating tests with full rest given between efforts. Average time of each interval was used to determine reliability and determine minimal detectable change.

Figure 1. 100-m start set up

Distance	Split Times	ICC	CV (%)	MDC
10-m	2.05 ±.13	.94 (.85-.98)	6%	.16s
20-m	3.32 ±.20	.97 (.90-.99)	6%	.25s
30-m	4.42 ±.30	.98 (.96-.99)	7%	.37s
40-m	5.45 ±.37	.99 (.97-1.0)	7%	.46s
50-m	6.42 ±.45	.99 (.97-1.0)	7%	.55s
60-m	7.32 ±.51	.99 (.98-1.0)	7%	.63s
70-m	8.21 ±.58	.99 (.98-1.0)	7%	.72s
80-m	9.08 ±.64	.99 (.97-1.0)	7%	.79s
90-m	9.90 ±.70	.99 (.98-1.0)	7%	.87s
100-m	10.73 ±.77	.99 (.99-1.0)	7%	.95s

Table 1. 100-meter acceleration 10-meter split times, reliability, and minimal detectable changes. 10-meter and 100-meter data are presented as mean ± standard deviation of the group.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the athletes and staff of US Speedskating and the Pettit National Ice Center.

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RESULTS

The mean and standard deviation were calculated for all 10-m splits of the 100-m acceleration trials. Inter-day reliability and MDC for all 10-m average split times were assessed and found to be very high when analysis of the average of two trials across the testing session. Intraclass correlation coefficients (ICC) and coefficients of variation (CV) were assessed (Table 1). The MDC at 95% CI was calculated as 1.96 x SEM √2. Reliability was considered acceptable in accordance with previous publications (1).

CONCLUSION

The purpose of the study was to establish the reliability and MDC of 100-m acceleration profiling in speed skating. The average of two trials was the best method of establishing reliable sprint times across individual 10-m segments and 100-m total time in 100-m on-ice acceleration profiling.

PRACTICAL APPLICATIONS

From the results of this study, it is recommended that when monitoring on-ice acceleration performance, the average of at least two trials should be used for analysis as well as, establishing performance goals for the training of the speed skating athlete.

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Appendix 4. Scientia Movens, Prague, Czech Republic, 2021 (Online).

Contribution Title: *Assessment and Monitoring of Lower Body Strength and Power in the Elite Female Speed Skater*

Name: Andrew Stuart
Supervisor: James Tufano PhD
University/Faculty: Charles University / Faculty of Physical Education and Sport
Keywords: Dynamic Strength Index, Periodization, Isometric Mid-Thigh Pull, Countermovement Jump, Speed skating

Theoretical Part:

Utilizing a strength and power assessment such as the dynamic strength index (DSI) can provide practitioners a means to evaluate the efficacy of the strength and conditioning program that is being prescribed for their athletes. In addition, these types of assessments can allow insight into setting individual and team standards, as well as individualizing resistance training programs to address deficiencies. The combination of using both isometric and is isoinertial assessments have been found to be effective means to evaluate strength qualities. Comparison of these two tests allow for practitioners to better determine the athlete's ability to apply force dynamically, in relation to the absolute force they can produce. This method has been shown to be valid and useful for guiding training prescription.

The purpose of this case study was to investigate the strength and power changes that occur from utilizing, programming, and monitoring dynamic strength index (DSI) in an elite female long track athlete. The athlete is an elite level long track female single distance sprint (32 years old, 65.6kg, 12 years of resistance and skating experience, and proven international competition success (1 Olympic bronze medal, 15 gold medals, one world record, and two world champion titles). This athlete completed three training phases of a periodized training program (10 weeks) with two testing sessions of dynamic strength index (DSI) testing using isometric mid-thigh pull (IMTP) and countermovement jump (CMJ). This training phase was a part of the Pre-Competition Phase of the annual training plan and followed an off-season and pre-season training cycle (sixteen weeks) sequential periodization training program.

Objectives:

For the purpose of this case study, the isometric assessment will include an isometric mid-thigh pull (IMTP) to measure the maximal force the athlete can produce. The dynamic measure will include a countermovement jump (CMJ) to measure the dynamic force the athlete can produce. These two measurements will be used to calculate the DSI ratio which will then aid in determine the appropriate training program to address the subject's deficiencies.

Methods:

This study involved a longitudinal single subject case study to assess the sensitivity of dynamic strength index testing to detect training induced changes. Furthermore, this study will investigate the changes to strength and power abilities following a resistance training program that is derived from the DSI ratio.

A warmup protocol of eight minutes of biking at 80-90 RPM followed by five minutes of a dynamic stretching routine was utilized prior to the testing. The subject was instructed to keep their hands on their hips during the countermovement jump and was instructed to perform a rapid deep and to jump as has as possible. The subject was allowed to self-select the depth that she believed would achieve the highest jump height. The subject performed a total of three countermovement jump. The force trace of the CMJ trials were inspected after each trial. The best trial was used for data collection and dynamic strength index calculation.

The subject then performed the isometric mid-thigh pull on a custom rack, using a posture that replicated the position at which they would start the second pull phase of the clean, with their knee and hip angles within 140-150°. Once the bar height was established, the athlete was instructed to stand in the center of the force platform, with their hands strapped to the bar using standard lifting straps. Athletes were also provided a standard lifting belt. The height of the bar and the resultant joint angles were replicated between trials and between testing sessions. The athlete was informed that the test would include two warmup sets at 50% and 75% effort with one-minute rest between efforts prior to starting the three trials at 100% effort with a two-minute rest between efforts.

The dynamic strength index (DSI) was determined by using the subject's peak force results from the countermovement jump and the isometric mid-thigh pull. The DSI variable reflected the dynamic force capabilities of the subject in relation to their absolute peak force capabilities. When investigating these capabilities, we can us the ratio between the two to determine what deficiencies the subject may have and address those through a properly individualized program. According to Sheppard et al., if the ratio is lower than .60, in conjunction with high peak force values in the IMTP; the subject may need to increase ballistic strength training. If the ratio is higher than .80, in conjunction with low peak force values in the IMTP; the subject may need to increase maximal strength. If the ratio is between these two values, the athlete may benefit from training in a concurrent manner to utilize both aspects. The data collection for this case study (Table 1) occurred during the Specific Preparatory Phase and Pre-Competition Phase, there were no major competitions that took place during this time. These specific phases were chosen due to the fact that the subject had completed a full off-season (General Preparatory Phase) which utilized a sequential periodization program that would have built a base for more specific training. During the data collection and program implementation the subject engaged in two strength and conditioning sessions per week, in conjunction with their sport training. The athlete was not advised to change any outside training regimens. Pre and posttest were conducted after 10 weeks of training (20 session) with 100% attendance and compliance.

Following the data collection, it was deemed that the subject had a DSI ratio of .71. According to the literature from Sheppard et al. this would suggest that the subject was not deficient in any one capability. Thus, the subject could train in a concurrent style training program which would develop power. The training program designed utilized a mixture of a mixed method, contrast, and complex training design that utilized the complete force-velocity curve. (Table 2.). As competition grew closer session-to-session changes per block of training had to be modified in response to increase on-ice sport training (Table 3). Following the implementation of this program a posttest was collected prior to the 2020-21 World Cup season beginning.

Results

For this case study, change in values for peak force in the IMTP, CMJ, and DSI were assessed for practical significance by comparing the change in absolute. Over the course of the ten-week training program the subject's peak force for the IMTP increased by 111.43 N and 51.62 N for the CMJ, resulting in a DSI ratio change of .1. Although this may seem not as

significant as expected; in weight room related performances the athlete saw an increase in back squat, power clean, and jump height performance.
For this case study, change in values for peak force in the IMTP, CMJ, and DSI were assessed for practical significance by comparing the change in absolute.

Discussion

Furthermore, the subject was prequalified for the 2021 ISU Speed Skating World Cup and 2021 ISU Speed Skating World Championship held in Heerenveen, Netherlands and did not perform in any competitions during the data collection and training timeline due to the SARS-CoV-2 pandemic. However, during the competition the subject was able to successful perform at a high level obtaining three top ten performances, one silver medal, five gold medal, two track record, and world champion in two different distances.

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Appendix 5. Accepted chapter contribution to the NSCA Developing Speed 2nd Edition

Roger Earle
Promotional opportunities for Developing Endurance, 2E and Developing Speed, 2E
Cc: reutebh & 1 more

December 5, 2023 at 1:17 PM
Details

Hello, Randy, Joshua, Will, Antonio, Greg, Kate, Rachel, Richard, Mike, Dave, Krista, Michael, JB, Dana, Matt, Boo, Irineu, John, Ken, Adam N, Adam R, Chris C, Loren, Chris J, Devan, PJ, Britt, Christina, Jeffrey, Brentan, and Andrew—

We just had our internal marketing meeting for *Developing Endurance, 2E* and *Developing Speed, 2E* and I am writing to ask if you would be interested in one (or both) of the following opportunities to promote the book that you have contributed to:

--Participating in an "Author Talk" session on Instagram where you would be 'interviewed' by HK's social media person (who is an S&C professional himself, so you would be able to "talk shop" with him) … here is an example: https://www.instagram.com/p/C0MthJnrE5l/
This session would be a pre-planned/scheduled event (some people would watch it live, but it would also be archived for people to watch later).

--Shooting and submitting a few short (1-3 minute) video clips where you explain a key topic (one per clip) related to your chapter … here are some examples:
https://us.humankinetics.com/blogs/articles/video-clips-from-the-warm-up
https://www.youtube.com/watch?v=cYOTjzjr_n8&list=PLcl1CFFoq_KN0cdkF77z7n1dytlmVPDgJ&index=65
https://www.youtube.com/watch?v=QM1cSy48Jpw
These clips are something you can do on your own with your phone (held vertically) and then emailed to me.

The "Author Talk" session would take place after the books release (May-June of next year) and the video clips can be shot/submitted anytime between now and February.

In exchange for your time, I can provide 4 free HK ebooks (for any book) for the "Author Talk" session or 1 free HK ebook per video clip. (NOTE: You will get a printed copy of the book that you have contributed to after it comes out.)

Alternatively, if you need CEUs for recertification by the end of this month, I can offer you free CE course(s)—4 or 1, like the ebooks—instead.

Let me know if you are interested!

Regards,

Roger

Roger Earle, MA, CSCS,*D, NSCA-CPT,*D, RSCC*D *(punctuated using NSCA house style)*
Senior Acquisitions Editor
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1607 North Market Street
Champaign, IL 61820

Email: RogerE@hkusa.com
Website: https://us.humankinetics.com/
Twitter: @roger_earle
LinkedIn: http://www.linkedin.com/in/rogerearle
Amazon author page: https://www.amazon.com/author/rogerearle

Appendix 6. The approved form of facility permission letter by the US Speedskating High Performance Director

US SPEEDSKATING

Concordia University Chicago
Institutional Review Board
7400 Augusta St
River Forest, IL 60305

I, Shane Domer, give Andrew Stuart (Head Strength and Conditioning Coach) permission to access the athletes of US Speedskating for the purpose of completing his research studies. In accordance with the health and safety measures that we already provide our athletes; all participants of the research studies lead by Andrew Stuart will be given the following:

1.) Athletes will have the option to opt out of data collection without penalty.
2.) Everything in our power will be done to mitigate any risks to athletes.
3.) All testing will be aligned with already scheduled training plans.
4.) Athletes participating in testing will have access to medical supervision and services per normal training circumstances and instances if needed.

Shane Domer

Shane Domer
High Performance Director
US Speedskating
5662 South Cougar Lane
Kearns, UT 84118

5662 South Cougar Lane | Kearns UT 84118 | O 801 417 5360 | F 801 417 5361

Appendix 7. Institutional Review Board Acceptance Letters

CONCORDIA UNIVERSITY CHICAGO
1864

7400 Augusta Street
River Forest
Illinois, 60305-1499
Fax 708-209-3167
www.CUChicago.edu

DATE:	December 21, 2021
TO:	Kristen Snyman, PhD
FROM:	Concordia University Chicago IRB
PROJECT TITLE:	[1851829-1] Reliability and Minimal Detectable Change of 100m Speed Skating Force-Velocity-Power characteristics
STUDY #:	
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	12/21/2021
EXPIRATION DATE:	12/21/2022
REVIEW TYPE:	Expedited

Thank you for your submission of the materials for this project. The Institutional Review Board has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received expedited review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the Modifications/Changes form for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the Adverse Events form for this procedure.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

If you have any questions, please contact IRB@CUChicago.edu. Please include your project title and study # in all correspondence.

CONCORDIA UNIVERSITY CHICAGO
1864

7400 Augusta Street
River Forest
Illinois, 60305-1499
Fax 708-209-3167
www.CUChicago.edu

DATE:	April 14, 2021
TO:	James Tufano, PhD
FROM:	Concordia University Chicago IRB
PROJECT TITLE:	[1732453-1] Between-Session and Between-Weekly Reliability of Post-activation Potentiation.
STUDY #:	
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	14 April 2021
EXPIRATION DATE:	15 March 2024
REVIEW TYPE:	EXPEDITED

Thank you for your submission of New Project materials for this project. The Institutional Review Board has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received EXPEDITED review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require that each participant receives a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this committee prior to initiation. Please use the Modifications/Changes form for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the Adverse Events form for this procedure.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

Please note that your first annual review is due APRIL 14, 2022.

If you have any questions, please contact IRB@CUChicago.edu. Please include your project title and study # in all correspondence.