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Performance Implications Of Rear Foot Movement In The Swimming Kick Start

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Performance Implications Of Rear Foot Movement In The Swimming Kick Start

by

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Abstract

The performance implications of changing rear foot joint angles in the kick start were evaluated using a replicated version of the Omega OSB11 starting block. Maximal effort dives were collected for twenty-six competitive swimmers. The block was equipped with two tri-axial force plates to differentiate between forces applied to the rear foot rest and forces applied to the block. Two high-speed video cameras recorded hind-foot eversion and dorsiflexion angles. Competitive swimmers with larger hind-foot eversion movement have larger lateral kick plate forces, longer kick plate times, and larger contributions of the kick plate to total impulse. These swimmers also have larger dorsiflexion movements. Improved start performance (defined by faster predicted time to two meters and higher normalized power) is associated with applying high normalized peak posterior kick plate force as quickly as possible while using the front leg as the dominant contributor to total impulse.

Keywords

swimming, performance, kick start, rear foot, eversion, dorsiflexion, omega OSB-11

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1 Introduction

1.1 Swimming Background

Competitive swimming became an organized sport in the early 19th century and quickly gained international popularity. This widespread popularity led to international competitions and regulations that controlled the methods used by swimmers during competition and training. For decades, swimming researchers have been investigating the physiology, biomechanics, psychology, and other components that contribute to swim training or performance.

Competitive swimming is a dynamic activity requiring an athlete to cover a specified distance as quickly as possible. Swimmers are ranked in order of fastest time to complete this distance. Their training and competition strategies aim to increase performance ability. Competitive swimming is comprised of four phases that contribute to race performance: the start, free swimming, turns, and the finish. The free swimming phase involves open kinetic chain movements, a movement in which the distal joint is free in space, whereas closed kinetic chain movements, a movement in which the distal joint is fixed, occur during the start, turn, and finish (Karandikar & Vargas, 2011). Effective training programs consist of focused sessions that address specific performance deficits within each race phase. Following a specific intervention, training methods are used to develop continuity between each phase to improve performance.

1.2 Training Adaptations

An athlete moves on land by applying force against the ground. This creates an equivalent ground reaction force and propels them forward. As described by Newton's third law of motion, an action (e.g. foot contact on the ground) creates a resultant force in the opposite direction that is equal in magnitude to the first (Bartlett & Bussey, 2013). An athlete running fast creates a higher ground reaction force compared to the magnitude created at slower running speeds. The joints and musculature of the lower limb apply an appropriate level of force in the desired direction for optimal control of movement. Athletes repeatedly practice these movements in different conditions to improve their performance abilities. These regular training sessions create proprioceptive and muscular adaptations that improve an athlete's speed, strength, and endurance capabilities (Sale, 1988). For example, a soccer player must practice their ball handling skill to assist in competitive situations when they are moving quickly and experiencing fatigue. Improving this skill improves the soccer player's performance.

Unlike movement on land, ground reaction forces do not exist in water. Instead, swimmers experience buoyancy (the upward force of water that is equal to the weight of the displaced water; McLean & Hinrichs, 1998) and drag (the force on a swimmer moving in water due to the rate of change of momentum of the water; Vorontsov & Rumyantsev, 2000). An athlete moves forward when the applied force is greater than the resistance of the water. Application of force is different in swimming compared to land activities. In water, specific techniques enable the swimmer to use the surface area of their upper and lower limbs to increase the amount of applied force while controlling the direction of movement (Sanders, 2007). For example, an open hand creates greater force against the water compared to moving a closed fist through the water at the same speed. A swimmer coordinates their upper and lower limbs throughout each phase of a swimming stroke to effectively move forward.

Similar to training programs of land-based sports, competitive swimming training programs aim to create physiological adaptations that improve performance at competitions. Swim programs involve phases of high volume, high frequency, and high intensity swimming. These are defined as total distance completed, number of training sessions, and rate of energy expenditure, respectively. High intensity training appears to benefit performance more than high volume training (Mujika et al., 1995). For example, one study observed that there were no performance differences between competitive swimmers that trained 1.5 hours each day at higher intensity compared to a group that trained 3 hours each day (Costill et al., 1991). Despite this evidence, it is common for competitive swim programs of elite level athletes to report training volumes greater than 10,000 meters (4+ hours) over two sessions, each day. High volume training of competitive swimmers causes normal physiological responses to stress (including elevated levels of serum cortisol, creatine kinase, and resting diastolic blood pressure;

Kirwan et al., 1988). Despite elevated stress responses to high volume training, athlete performance was unaffected. This ability to tolerate repeated high volume training sessions while maintaining performance levels, without detrimental physical responses, is an important capability of swim training (Costill et al., 1991; Kirwan et al., 1988).

1.3 Statement of the Problem

Similar to athletes training on land, swim training causes muscular adaptations of an athlete's swimming technique; enabling them to swim faster. Kicking techniques used in water involve the foot as a propulsive tool to increase applied force against the resistance of water. The foot and ankle of experienced swimmers moves passively while transferring force created by musculature at the hip and knee joints (Sanders, 2007; Zamparo, Pendergast, Termin, & Minetti, 2002). This improves kicking speed and contributes to overall swimming speed.

A large determinant of an athlete's performance is the free swimming component. However, performance is also determined by the start and turn components of the race. In these components, the swimmer must push off the starting block and walls. The ability to supinate the foot contributes to effective transfer of muscular forces during closed kinetic chain activities (Fuller, 2000), such as these starting block and turn components. In contrast, optimal free swimming technique requires increased ankle flexibility with large plantarflexion range of motion throughout the kicking movement (McCullough et al., 2009). Repeated high volume training creates physiological adaptations, specifically in the foot and ankle (i.e. increased plantarflexion range of motion) that improve performance in the kicking component of the free swimming phase (McCullough et al., 2009). However, large plantarflexion and eversion range of motion may not be ideal for force application in closed kinetic chain activities (Donatelli, 1987), such as the start and turn phases. This investigation evaluates the performance implications of changing rear foot joint angles during the starting block phase of swimming competitions.

2 The Foot

Research evaluating the foot during sprint starts and sprint running is prevalent in the literature due to its significant influence in the control of static stance and dynamic function (Murley, Landorf, Menz, & Bird, 2009). During the block start, an athlete generates force via their hip and knee extensor musculature, and transfers it through their feet to the starting block. The dynamic ability of the foot is important because it can adapt its structure to provide effective force transmission and improve dynamic function of the lower limbs. Therefore, literature evaluating the foot in dynamic function is important to understanding the function of a swimmer's foot on the starting block.

2.1 Basic Anatomy and Arches of the Foot

The foot is a complex biomechanical structure that aids in impact absorption and assists in force transfer during dynamic function on land (Snook, 2001). The skeletal structure of the foot and ankle is comprised of tarsals and metatarsals. The tarsal bones include the: calcaneus, talus, navicular, cuboid, lateral cuneiform, intermediate cuneiform, and medial cuneiform. The tarsals lie proximal to, and articulate with, the metatarsals; these articulate with distal phalanges, forming the foot and ankle. Arrangement of the tarsals, metatarsals, ligaments, and tendons of the foot create three arches: the transverse arch, the lateral longitudinal arch, and the medial longitudinal arch. These arches are designed to provide stability to the foot when weight-bearing, as well as assisting in dynamic function (Franco, 1987). Despite the fact that there are three arches of the foot, the medial longitudinal arch is considered the arch of greatest clinical significance because the lower limb depends on the base of support provided by the medial longitudinal arch; any problems originating from this arch ultimately affect lower limb function (Franco, 1987; Figure 1).

Figure 1: Medial longitudinal arch

2.2 Arch Development

The bony arrangement of a foot is impacted by many factors, including musculoskeletal development, which is influenced by activities during skeletal maturation (Rao & Joseph, 1992). Many competitive swimmers engage in aquatic activity and swimming during their early childhood. The function of the foot in water is different compared to land activities and the arch may develop differently dependent on childhood activity.

Infants are born with flexible flat feet and an arch develops with age. Research evaluating static footprints of children (ages 4-13) report a significantly increased prevalence of flat-feet in shod children compared to unshod children; 8.6% compared to 2.8%, respectively (Rao & Joseph, 1992). Furthermore, results indicated that children habitually wearing closed-toed shoes have a greater incidence of flat-feet, 13.2%, compared to children habitually wearing slippers, 8.2%, or sandals, 6%. Rao & Joseph (1992) concluded that wearing shoes in early childhood is detrimental to the formation of a normal medial longitudinal arch. Furthermore, recent research suggests the importance of muscular strength and barefoot mobility to arch development (Cappello & Song, 1998).

The function of the foot is different during swimming compared to land activity. Investigations of the influence of footwear to arch development may shed light on our understanding of arch development in swimmers that engage in regular aquatic activity during early childhood. A direct investigation of arch development in swimmers has yet to be performed; however, the findings of Rao & Joseph (1992) suggest that arch development may be influenced by their footwear and/or activity. Further investigations of competitive swimmers are necessary to determine the influence of activity to arch development.

2.3 Foot Morphology

The bony arrangement of the foot and ankle plays an important role in the dynamic function of the musculature and joints, including structures proximal to the foot that rely on a stable base of support (i.e. ankle, knee, hip, and low back; Franco, 1987). Therefore, research evaluating the function of different foot morphologies is important to understanding the function of a swimmers foot on the starting block.

Pes cavus is a term that describes a high-arched foot and relative hypomobility with weight-bearing (Figure 2), whereas pes planus, or a flexible flat foot, results in excessive pronation, and is a term commonly used in medical literature to describe a collapse of the medial longitudinal arch (Figure 3; Franco, 1987). A flexible flat foot describes a foot with an apparent medial longitudinal arch during non-weight bearing conditions, however the arch immediately disappears once weight bearing. In contrast, a rigid flat foot describes a foot with a collapsed medial longitudinal arch in both weight-bearing and non-weight-bearing conditions.

Figure 2: A high-arched foot

Figure 3: A flexible flat foot

Defining foot morphology helps to improve the diagnosis and the development of effective treatment to address specific deficits in the lower limb (D. S. Williams, Mcclay, & Hamill, 2001). In addition, defining foot morphologies helps to describe performance implications of athletes with different foot morphologies. It is important to note that many individuals with high-arched or flexible flat feet are functionally stable and without pain (Neely, 1998). Therefore, interventions to correct bony arrangement are only indicated for patients with complaints of discomfort or pain caused by their foot morphology. However, intrinsic muscular training programs improve an athlete's dynamic ability to support the medial longitudinal arch and assists the foot to create a rigid lever that is optimal for start block performance (Mulligan & Cook, 2013)

2.3.1 Methods of Foot Classification

In order to classify feet, quantitative measures or specific qualitative observations must identify numerical ranges or characteristics that are unique to specific foot morphologies. There are four common methods used to evaluate foot morphology: visual inspection, anthropometric values, footprint parameters, and radiographic evaluation (Razeghi & Batt, 2002).

2.3.1.1 Visual Inspection (Qualitative Assessment)

Physical therapists and clinicians often observe a patient's foot in both static stance and dynamic function (e.g. gait) to further assess the lower limb. Compression and collapse of the medial longitudinal arch is observed by inspecting the foot from anterior, medial, and/or posterior views. Information obtained from observing the arch can help determine future treatment and interventions. Furthermore, the movement observed as compression or elevation of the medial longitudinal arch is, more specifically, a resultant of pronation and supination movement along the sub-talar joint axis (Payne, Munteanu, & Miller, 2003).

A study evaluating the consistency of foot type classification between three examiners indicated adequate reliability, with an inter-rater reliability (kappa value) of 0.724 (Dahle, Mueller, Delitto, & Diamond, 1991). In contrast, another study evaluating the consistency of visual assessments of arch height indicated a low level of agreement (significant variability; kappa values of 0.32-0.79 for flat feet and 0-1.0 for high arched feet) between clinicians (Cowan, Robinson, Jones, Polly, & Berrey, 1994). The latter study had a larger number of participants (246 compared to 77) and examiners (6 compared to 3), indicating differences between studies. These contrasting studies highlight the need for quantitative methods of assessing arch height in order to classify foot morphology with greater reliability.

2.3.1.2 Anthropometric Values (Quantitative Assessment)

Quantitative assessments of the foot arch have indicated moderate to strong reliability and increased the accuracy of classifying foot morphology. The navicular tuberosity is particularly important as an accurate determinant of sub-talar joint movement (Griffin, Miller, Schmitt, & D'Août, 2013). Common measures of the navicular tuberosity include: height (at weight-bearing), drop (difference of height from non-weight-bearing to weight-bearing), and drift (translational shift)(Vinicombe, Raspovic, & Menz, 2001).

Navicular height indicates the height of the navicular tuberosity in a relaxed weight-bearing stance. Navicular height investigations have reported both, strong reliability (ICC=0.8) and moderate reliability (ICC=0.33 to 0.76), to evaluate the medial longitudinal arch (Vinicombe et al., 2001; D. Williams & McClay, 2000). The navicular drop test is commonly used in the literature and evaluates the change in height of the navicular tuberosity between sub-talar neutral and weight-bearing stance. Specific thresholds of navicular drop that indicate abnormalities have ranged between 10mm, 13mm, and 15mm (Beckett, Massie, Bowers, & Stoll, 1992; Cote, Brunet, Gansneder, & Shultz, 2005; Snook, 2001). Fortunately, a general consensus identifies ranges of pronation that categorize different foot morphologies related to medial longitudinal arch height, including: excessive pronation (flexible flat foot) defined by values greater than 10mm, normal pronation defined between 4 and 9mm, and pes cavus (hypomobility) defined by values less than 4mm (Beckett et al., 1992; Cote et al., 2005; Franco, 1987; Griffin et al., 2013; Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999; H. B. Menz, 1998; Snook, 2001; Vinicombe et al., 2001). Navicular drift measures the medial translation of the navicular tuberosity in the transverse plane as indicated by a medial bulge that is characteristic of a pronated foot (Donatelli, 1985); however the reliability of this test has not yet been evaluated.

In dynamic gait function, the foot moves into pronation to absorb initial impact with the ground (Donatelli, 1985). The movement of the foot and ankle is quantified by calculating the change of joint angles. The medial longitudinal arch angle and achilles angle (hind-foot inversion/eversion) are measures that have provided valuable data in literature evaluating the foot in dynamic function (McPoil & Cornwall, 1996; Menz & Munteanu, 2006). The medial longitudinal arch angle is measured by digitizing three landmarks on the medial side of the foot (Saltzman, Nawoczenski, & Talbot, 1995). This can present difficulties during the collection of dynamic function data as it can be difficult to observe these landmarks continuously. The hind-foot inversion/eversion angle is measured by digitizing and calculating angles of the hind-foot and lower leg throughout movement using a camera or instrumentation placed posteriorly (Stacoff, Kaelin, Stuessi, & Segesser, 1989). The hind-foot inversion/eversion method of quantifying the function of the foot is useful for dynamic events, such as the block start, as the data can be collected from a posterior view of the foot.

2.3.1.3 Footprint Parameters

The footprint is a commonly used measure to predict the height of the medial longitudinal arch because it is a non-invasive, cost effective, and simple technique. Investigations of the footprint indicate progressive contact of the inferior aspect of the foot in response to compression of the medial longitudinal arch (Kanatli, Yetkin, & Cila, 2001; Mathieson, Upton, & Birchenough, 1999; Qamra, Deodhar, & Jit, 1980). Evaluating footprint parameters requires a stable base of support (e.g. flat terrain) for the participant to contact in order to collect the necessary foot pressures. This becomes a limitation if the dynamic function that is investigated is not on flat terrain, such as a starting block.

2.3.1.4 Radiographic Evaluation

Radiographic imaging is used to accurately evaluate foot and ankle structures and is considered the gold standard for providing valuable information regarding bony arrangement and structural deformities (Saltzman et al., 1995). Radiography is typically used to further investigate the etiology in a patient complaining of discomfort or pain. Unfortunately, it is a costly method of evaluation. Research has compared alternative tests to radiographic standards and results have indicated anthropometric values and footprint parameters that are strongly correlated with radiography (D. Williams & McClay, 2000).

3 Basic Mechanics of the Foot

Normal foot pronation aids impact absorption and effective mobility across changing ground terrain, whereas supination is important to create a rigid lever for toe-off and propulsion (Bolgla & Malone, 2004; Franco, 1987; Kim & Lee, 2013; Neely, 1998). For example, in the initial weight-bearing stance phase of gait, the medial longitudinal arch is compressed and the sub-talar joint moves into pronation; the talus shifts into adduction and plantarflexion, and the calcaneus everts. In the last 50% of the stance phase of gait, the sub-talar joint returns to a supinated position (McPoil & Cornwall, 1996). The talus shifts into abduction and dorsiflexion and the calcaneus inverts (Griffin et al., 2013).

During the initial stance phase of gait, excessive pronation delays the onset of supination; interfering with effective foot mechanics for propulsion (Aquino & Payne, 2001; Griffin et al., 2013). Specifically, excessive pronation reduces the effectiveness of the Windlass mechanism: the plantar fascia is stretched when the first metatarsophalangeal joint (FMTP) shifts into passive dorsiflexion (Fuller, 2000). For example, the onset of medial longitudinal arch movement occurred at a mean FMTP dorsiflexion angle of 4.1 degrees, compared to 20.4 degrees in the delayed onset group (Kappel-Bargas et al.,1998). The duration that the Windlass mechanism produced tension in the medial longitudinal arch was also reduced in the delayed onset group. In addition, a flexible flat foot significantly increases medial plantar pressures (2^{nd} and 3^{rd} metatarsal contact area) with increasing gait velocities, with medial pressures recorded of 5.4 psi, 6.7 psi, and 8.1 psi at approximate gait velocities of 3.0 km/hour, 4.0 km/hour, and 5.0 km/hour, respectively (Kim & Lee, 2013).

3.1 Pronation, Supination, and the Sub-Talar Joint

Proper function of the foot in weight-bearing activity relies on the sub-talar joint (Manter, 1941). The sub-talar joint is the axis of rotation for pronation (dorsiflexion, abduction, and eversion of the foot) and supination (plantarflexion, adduction, and inversion of the foot). In weight-bearing stance, ground reaction forces occur at the medial calcaneal tubercle and the lateral forefoot (base of the 5^{th} metatarsal and lateral metatarsal heads; Figure 4). These ground reaction forces control the rotational equilibrium of supination and pronation moments along the sub-talar joint axis (Kirby, 1989). In feet with normal arches, the medial calcaneal tubercle is located medially to the sub-talar joint axis; forces applied at this location produce supination moments, while the lateral forefoot is located laterally to the sub-talar joint axis and forces applied at this lateral location produce pronation moments. The location of the sub-talar joint in a relaxed static stance (a position of no significant rotational motion) represents rotational equilibrium between the ground reaction forces along the sub-talar joint axis (Kirby, 1989).

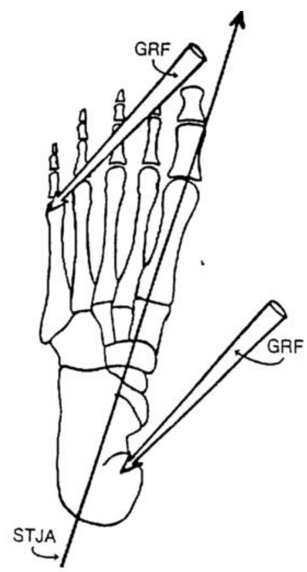

Figure 4: Plantar aspect of the foot, ground reaction forces (GRF) and sub-talar joint axis (STJA) in a normal foot (with permission from © Kirby, 1989)

In addition to ground reaction forces, internal forces created by musculature also affect pronation and supination moments at the sub-talar joint axis. In a normal foot, muscular attachments that insert medially to the sub-talar joint axis apply a supination moment when contracted, whereas muscular attachments that insert laterally to the sub-talar joint exert a pronation moment when contracted. The dynamic function of the foot is coordinated by effectively balancing the activation of these pronating and supinating muscle groups (Kirby, 1989).

A change in the bony arrangement of the foot results in medial or lateral deviation of the sub-talar joint; medial deviation is observed in pes planus, or flat feet, while lateral deviation is observed in pes cavus, or high-arched feet. These deviations of the sub-talar joint alter the supination and pronation moment arms, of the ground force reaction and musculature. This results in a shift in the location of rotational equilibrium (Kirby, 1989; Payne et al., 2003). Furthermore, an excessive shift in the location of rotational equilibrium (such as those found in excessive pronators or supinators) can alter directional forces of musculature. For example, a foot with a large degree of medial deviation translates the sub-talar joint axis medially and can shift the insertion of a medial muscle to the lateral side of the axis (Kirby, 1989). This lateral shift changes active supinators to pronators when contracted.

Fluid movement of the foot into a pronated position is necessary for normal dynamic function. Normal pronation of the foot creates an ‘unlocked’ and ‘loose packed position’ which assists in impact absorption and improves mobility across changing ground terrain. Upon return of the sub-talar joint into neutral alignment, or supination, the foot becomes ‘locked’. This ‘locked’ structure maximizes foot stability and provides a rigid lever for force transfer (Cote et al., 2005; Franco, 1987; Neely, 1998; Snook, 2001).

During the starting block phase of competitive swimming, swimmers must apply large magnitudes of force to the block. Theoretically, a foot in a supinated position is more effective to apply force during the starting movement than a foot in a pronated position.

3.2 The Foot in Competitive Swimming

In swimming, a swimmer’s foot aids in propulsion and is no longer used as a base of support, when compared to land activity. Skilled competitive swimmers develop a kicking technique that is hydro-dynamically efficient. In the underwater dolphin kick, swimmers coordinate active hip and knee, and passive ankle undulations to create a body wave that increases in velocity towards the distal segments (Atkison, Dickey, Dragunas, & Nolte, 2014; Sanders, 2007). This body wave results in faster kicking speed because of the increased applied force. Effective muscular recruitment at the hip and knee joints contributes to increasing velocity of the body wave (Figure 5). Similar to the underwater dolphin kick, the flutter kicking technique results in faster kicking speed as a consequence of increased applied force from the musculature. The body wave, however, is unique to the underwater dolphin kick. In an effective flutter kick, the trunk is a rigid structure and propulsion occurs from flexing and extending the hip and knee joints, while alternating the legs (Sanders, 2007; Figure 6).

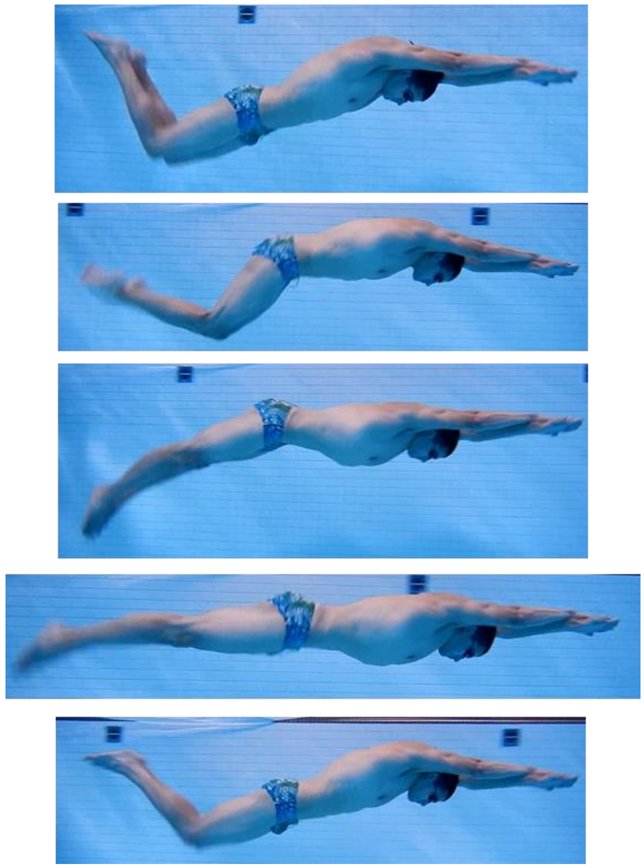

Figure 5: Underwater dolphin kicking technique (from top image to bottom shows the progression from a down-kick to an up-kick). The ankles maintain a plantarflexed position and are at end-range of plantarflexion motion during the initiation of the down kick.

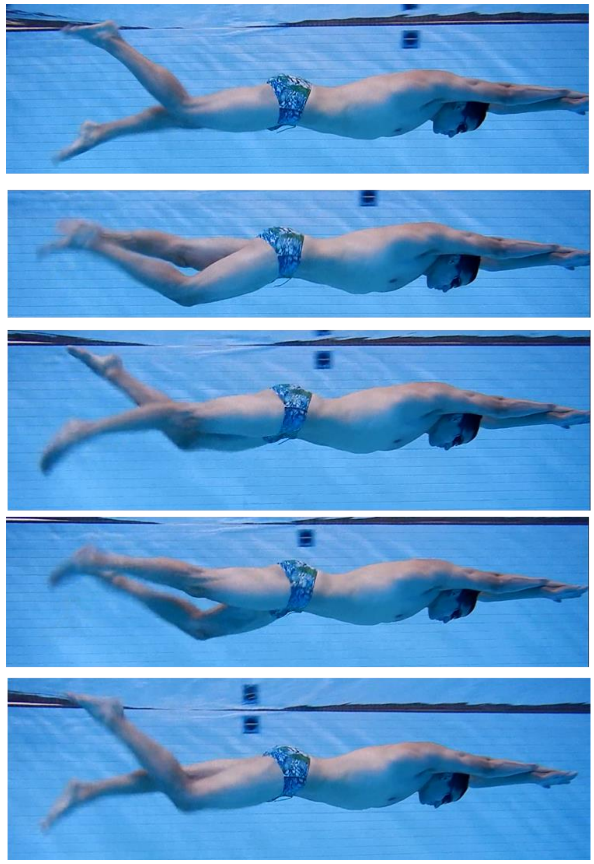

Figure 6: Underwater flutter kicking technique

Ankle movement during the up-kick and the down-kick is similar in both kicking techniques (Sanders, 2007). The ankle joint maintains a plantarflexed position throughout the kick cycle (Atkison et al., 2014). During the down-kick, the ankle is plantarflexed to its end-range of motion and passively dorsiflexes within a plantarflexed position (Sanders, 2007). During the up-kick, the ankle shifts from the already plantarflexed position and achieves a maximum end-range of motion in the plantarflexed position (Sanders, 2007).

Research evaluating the underwater dolphin and flutter kicking techniques in novice swimmers reported excessive hip flexion, inadequate hip extension, excessive knee flexion, and inadequate plantarflexion range of motion compared to experienced swimmers (Sanders, 2007). These authors suggest that the kicking technique of beginner swimmers is influenced by pre-existing and familiar movement patterns, such as walking. This may contribute to beginner swimmers displaying excessive dorsiflexion range of motion and inadequate plantarflexion sufficient for flutter kicking (Sanders, 2007). With increased exposure and experience, swimmers achieve effective techniques for performance, including optimal plantarflexion range of motion (McCullough et al., 2009; Sanders, 2007).

Similar to athletes of land-based sports, competitive swimming programs aim to develop muscular adaptations by using different methods, including training sets of repeated swimming and kicking efforts. In addition, programs include the use of equipment, such as fins, to improve kicking performance. The fin is worn like a shoe, or slipper. The ankle opening of the fin ends dorsally at the tarsals and posteriorly at the Achilles tendon. Fins increase the surface area of the foot, thus increasing the water resistance that is experienced with each kick (Figure 7). This requires greater muscular recruitment from the hip and knee joints to apply force. The increased applied force results in greater propulsion and speed. Fin training interventions improve muscular recruitment (Pendergast, Mollendorf, Logue, & Samimy, 2003) and neurological adaptations created by speed assistance (Zamparo et al., 2002). However, the increased resistance of water created by wearing fins will apply force to the tarsal joints at their end range of plantarflexion motion. These training methods create adaptations to a swimmers foot and ankle that improve their kicking and free swimming ability. Unfortunately, these adaptations may negatively impact a swimmers ability to effectively apply force on the starting block.

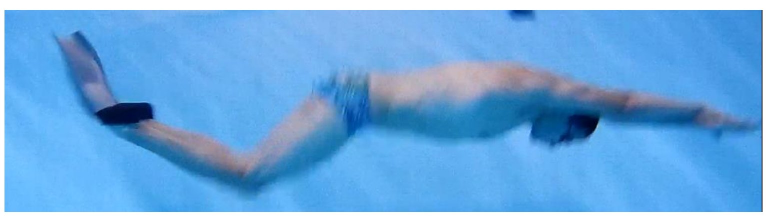

Figure 7: The down-kick of the underwater dolphin kick wearing fins. The ankles are positioned at the end-range of plantarflexion motion during this down-kick phase of the underwater dolphin kick.

4 Block Start Performance

Biomechanical evaluations of the block start in swimming and running aim to improve performance ability. It is important to understand the overall race objective when evaluating and quantifying the performance of each race component. The outcome of a race is solely determined by time to completion. However, an athlete's performance in the block phase influences the remainder of their race. Therefore, a block start performance measure must not only represent the athlete's ability to start, but also represent the influence of the start on the overall race. An improvement in this measure should indicate positive contributions, and suggest improvement, to overall race performance.

The starting block was introduced in running competitions as early as 1937. The crouch start is a term used to describe a runners stance for optimal start performance (Majumdar & Robergs, 2011; Salo & Bezodis, 2004). In the crouch start, the runner's feet are staggered and positioned against the starting block. Their body weight is supported by their fingers which are placed on the track behind the starting line and their center of mass is shifted forward. There has been an increase in research investigating sprint start performance due to the significant contribution of the block start on overall performance.

In swimming competitions, the Omega OSB9 starting block was a slanted platform used internationally for years. In 2008, Omega introduced the OSB11 model which was the first starting block in swimming to have a rear footrest. The introduction of starting blocks in running events, and the rear footrest in swim competitions, have drastically improved performances in their respective sporting events due to the increased ability of an athlete to apply horizontal force against a footrest (Majumdar & Robergs, 2011; Ozeki, Sakurai, Taguchi, & Takise, 2012). Despite many differences between sprint running and swimming events, there is information from sprint running block start literature that is valuable to understanding the block start phase in swimming.

4.1 Sprint Running Block Start Performance Measures

Successful athletes complete the race distance in the shortest amount of time. This requires that the athlete achieves a peak running velocity early in the race. The block phase is the first phase of the race; it spans from the first sound of the starter's gun and ends at the athlete's last point of contact with the block. Prior to movement during the block phase, athletes begin in a static stance. During the block phase, athletes are required to create forces large enough to propel their center of mass forward. The second phase of the race is the acceleration phase, which begins at the last point of contact with the block and ends 15 meters from the starting line (Hunter, Marshall, & McNair, 2005). Successful sprinters achieve a peak running velocity early in this acceleration phase (Blazevich, 2007) through an optimal combination of stride frequency and length. Approaching the end of the acceleration phase, a successful athlete's center of mass is increasing in velocity and decreasing in acceleration. This indicates that the athlete is approaching peak velocity and will attempt to maintain that velocity for the remainder of the race.

Until recently, no single parameter has effectively predicted start performance. Block velocity, the athlete's horizontal velocity as they leave the block, is the most commonly used measure in literature and is calculated from the sprinters horizontal (anterior-posterior) impulse at the last point of contact with the block (Guissard, Duchateau, & Haunaut, 1992; Mendoza & Schöllhorn, 1993; Mero & Komi, 1990; Mero, Kuitunen, Harland, Kyrolainen, & Komi, 2006; Vagenas & Hoshizaki, 1986). Other common performance measures include the time to a specific distance (Mendoza & Schöllhorn, 1993; Mero et al., 2006; Schot & Knutzen, 1992; Vagenas & Hoshizaki, 1986), velocity at a specific distance (e.g. 15m) or event (e.g. first-step) (Mero & Komi, 1990; Salo & Bezodis, 2004; Schot & Knutzen, 1992), and peak or average block acceleration (Delecluse et al., 1995; Guissard et al., 1992; Mendoza & Schöllhorn, 1993).

When evaluating start performance, block velocity has been an appropriate measure for start performance due to the high demands requiring peak accelerations from a static position. Bezodis et al. (2010) investigated ten performance measures in a sprint event. They indicated that block velocity, calculated from the anterior-posterior impulse (the integral of force with respect to time), is misleading as a start performance measure. An increased block velocity (impulse) could be caused by either an increase in the net propulsive force generated or by an increase in the athletes' push duration on the block (block time). At first glance, an increased push duration on the starting block appears to contradict the overall 'shortest time' objective in sprint events.

Instead, Bezodis et al. (2010) suggest that maximal power production during the block phase is a dominant measure for performance. Power, the integral of the rate of change of energy (work) with respect to time (Winter, 1979), addresses the confounding factors created by block velocity (Bezodis et al., 2010). Power is critical in every phase of a sprint event. The increased energy requirements needed to produce large bouts of power is outweighed by reducing the time spent at submaximal velocities during the block and acceleration phases. Furthermore, Bezodis et al. (2010) indicate that performance measures from beyond block exit during running are not only related to the block phase, but are also due to the significant influence of stride technique to reach the specified distance.

4.2 Swimming Block Start Performance Measures

In swimming competitions, the start phase begins at the sound of the start signal. The definition of end of the start phase, however, has been inconsistent in swimming literature. A review of all research evaluating the swimming block start, including investigations of appropriate performance measures, was completed to accurately report on current literature. Refer to Appendix A for a list of all investigations, as well as their performance measures and main findings.

A swimmers' time to a specific distance has been a common performance measure used in research. Unfortunately, this specific distance, used to indicate the end of the start phase, has used a wide range of values from 5 to 15 meters (Hardt, Benjanuvatra, & Blanksby, 2009; West, Owen, Cunningham, Cook, & Kilduff, 2011). Other common performance measures include horizontal take-off velocity (Arellano, Pardillo, De La Fuente, & Garcia, 2000; Benjanuvatra, Edmunds, & Blanksby, 2007) and block time (Arellano, Llana, Tella, Morales, & Mercade, 2005; Guimaraes, Alegre, & Hay, 1985). In addition to these performance measures, multiple kinetic and kinematic output variables have been identified as contributors to start performance. Common kinetic variables have included: average horizontal and vertical velocity (Guimaraes et al., 1985; Honda, Sinclair, Mason, & Pease, 2012), horizontal and vertical impulse (Benjanuvatra, Lyttle, Blanksby, & Larkin, 2004; Breed & Young, 2003; Vint, Hinrichs, Riewald, Mason, & Mclean, 2008), peak horizontal and vertical force (Honda et al., 2012; Slawson, Chakravorti, Conway, Cossor, & West, 2012), rate of force development (West et al., 2011), average and peak power (Mason, B. Alcock, A. Fowlie, 2002), and horizontal and vertical entry velocity (Seifert et al., 2010). Common kinematic variables have included: take-off angle (Arellano et al., 2000), entry angle (Chen & Tang, 2005; Holthe & McLean, 2001), and flight distance (Galbraith, Scurr, Hencken, Wood, & Graham-Smith, 2008; Ozeki et al., 2012).

A swimmer's time to 15 meters is the combined result of block time, flight time, underwater time, and transition time (Schnabel & Kuchler, 1998). Each of these components influences the start performance when it is defined by time to 15 meters. Race analysis of the 1999 Pan-Pacific Swimming Championships indicated that a swimmers time to 15 meters significantly predicted outcomes in all races (Mason & Cossor, 1999). These results suggest the importance of propulsive efficiency throughout each race component in determining race outcome. Soon after, swim start literature identified problems with using time to 15 meters as an indicator of start performance. Performance measures located beyond the flight phase are influenced by entry mechanics and underwater technique (Cossor & Mason, 2001; Mason & Cossor, 1999; Ruschel, Araujo, Pereira, & Roesler, 2007). Therefore, a swimmers' efficiency in the underwater and transition components can influence their time to 15 meters regardless of their ability on the starting block. Higher take-off velocities were found in block starts compared to push-offs from the wall, however these velocity differences were eliminated by the time the swimmer entered the transition and free swimming components (Takeda, Ichikawa, Takagi, & Tsubakimoto, 2009). These findings highlight the importance of a swimmer's combined efficiency in each component for race performance. Swimming start block research must identify performance measures that directly represent a swimmer's capability on the starting block. An appropriate starting block measure should suggest that an improvement in this measure is representative of an improvement in race performance.

In addition to problems with using performance measures found beyond the flight phase, there have been inconsistencies defining an optimal performance measure on the starting block. Horizontal (A-P) take-off velocity, calculated using the impulse-momentum relationship with respect to time on the starting block, is a common performance measure in swimming research. Similar to problems observed with sprint running block velocity (section 4.1), horizontal take-off velocity is a misleading performance measure due to the influence of time. A higher take-off velocity can be caused by longer block times, which contradicts the performance goal of 'fastest time to completion' in swimming races. The complication with horizontal take-off velocity is supported by research evaluating start performances between recreational and elite level swimmers; both groups showed similar take-off velocities during the block phase, however elite swimmers had larger horizontal impulses and faster block times (Benjanuvatra et al., 2007).

In addition to horizontal take-off velocity, block time is another commonly used measure of start performance; an evaluation of 1657 block starts at international and national level competitions used block time as the sole measure of start performance (Garcia-Hermoso et al., 2013). Problems with using block time as a start performance measure have been identified in research evaluating a swimmer's weighting, or lean, on the starting block. This has been termed front-weighted, neutral-weighted, and rear-weighted depending on the location of a swimmers center of mass. Results of two independent evaluations have indicated that front-weighted starts have faster block times, however neutral and rear-weighted starts have higher horizontal velocity (Welcher, Hinrichs, & George, 2008) and faster times to 5 and 15 meters (Barlow, Halaki, Stuelcken, Greene, & Sinclair, 2014). These results suggest the importance of combining performance measures in order to appropriately evaluate swimmers efficiency during the block start and its contribution to their race performance.

5 Foot Mechanics on the Starting Block

5.1 Sprint Running Start Block

Since its introduction to athletic competitions, the starting block and subsequent start performance research has gradually led to improved sprint running performances (Majumdar & Robergs, 2011) . Starting block research suggests medium block spacing and hips held moderately high for optimal performance (Harland & Steele, 1997). Furthermore, research evaluating optimal rear and front knee joint angles indicates 90˚ and 130˚, respectively (Harland & Steele, 1997). Adopting this technique contributes to effective start block performance which strongly influences an athlete's performance in sprinting events. There is limited research evaluating performance implications of foot movement on the starting block. However, gait and jumping research can be used to further understand the implications of rear foot movement on block start performance.

Evaluations of the ankle in jump performance indicates a significant positive correlation between ankle joint stiffness and ankle torque in rebound jumps (Yoon, Tauchi, & Takamatsu, 2007).They suggest that ankle stiffness in the eccentric phase of a rebound jump is important to produce greater torque and, ultimately, improve jump performance. Furthermore, evaluations of the ankle joint in the sprint running block start report that the ankle absorbs energy as it undergoes dorsiflexion (eccentric work) in the first 30% of stance before generating energy by plantarflexing (concentric work) (Charalambous, Irwin, Bezodis, & Kerwin, 2012). Eccentric work is the collapse of the lower limb controlled by the contraction of the ankle plantarflexors, whereas concentric work is the release of stored elastic energy and/or contraction of the ankle plantarflexors. Dynamic ankle stiffness has been correlated with performance measures, including vertical velocity and contact time (Charalambous et al., 2012), suggesting a positive relationship between ankle joint stiffness and starting block performance.

5.2 Swimming Start Block

In the shorter sprint events, the start can significantly impact overall race performance. The Omega OSB11 start block features a main platform and an adjustable rear footrest angled at 30 degrees to the main platform. This footrest improves the swimmers potential to achieve greater force in the anterior-posterior direction, similar to sprint running blocks. The OSB11 starting block has created a new start technique, termed the kick start. Research has indicated that the kick start improves a swimmer's start performance compared to the traditional swimming grab and track starts on the OSB9 slanted platform (Ozeki et al., 2012).

In recent years, a number of studies have investigated the Omega OSB11 starting block, including: differences between the new OSB11 model and the original OSB9 (Garcia-Hermoso et al., 2013), optimal joint angles (Slawson et al., 2012), and optimal rear footrest positioning (Honda et al., 2012; Slawson et al., 2011; Takeda, Takagi, & Tsubakimoto, 2012). This biomechanical research has improved the knowledge pertaining to optimal measures for improved start performance. However, previous research has not yet investigated foot and ankle mechanics of competitive swimmers during the start.

5.2.1 The Kick Start Technique

The kick start technique describes a swimmers set up position and stance on the Omega OSB11 starting block. Similar to the track start on traditional OSB9 slanted starting blocks, the swimmer is in a crouched position and their hips are positioned high. The swimmer places one foot at the most anterior aspect of the block, flexing their toes over the anterior edge of the block, and their rear foot is positioned against the rear foot rest. The swimmer places their hands on either side of their front foot and grasps the anterior edge of the block. Research evaluating optimal rear and front knee joint angles at set up indicates 100 to 110 degrees and 135 to 145 degrees, respectively (Slawson et al., 2012). This investigation also indicated that swimmers maintain their knee joint angles by adjusting their rear foot height; when the footrest position is shortened, swimmers shift their foot to a lower position on the foot rest allowing them to maintain optimal knee joint angles. In addition, swimmers should adopt a neutral-weighted or rear-weighted starting position as indicated by reduced time to 5 meters and 15 meters, despite longer block times, compared to front-weighted starts (Barlow et al., 2014).

The typical placement of the rear foot adopted by experienced swimmers, and the stance suggested in literature, places the foot in contact with the top half of the rear kick plate (Slawson et al., 2012). During the propulsive phase, the foot plantarflexes and the first metatarsophalangeal joint (FMTP) shifts into passive dorsiflexion. This suggests that the propulsive phase is assisted by the Windlass mechanism, which increases stiffness and stores elastic energy in the foot, by stretching the plantar fascia. The toes of the front foot are flexed over the edge of the block during set- up. Therefore, swimmers use the anterior edge of the block to apply posterior force with limited influence of the FMTP and the Windlass mechanism (Figure 8).

Figure 8: The position of swimmers on the Omega OSB11 starting block prior to movement

Despite numerous investigations that evaluate the swimming start block performance, current literature has yet to evaluate the performance implications of changing rear foot joint angles of competitive swimmers throughout the kick start on the Omega OSB11 start block.

6 Methods

A total of 26 individuals, fifteen males and eleven females, between the ages of 18 and 24 participated in this study. All subjects were experienced swimmers currently competing at the varsity-level or higher. Approval for this study was obtained from the Research Ethics Board at the University of Western Ontario (Refer to Appendix B for the Ethics Approval Notice for this study). In addition, participants were given verbal and written explanations of all risks involved with the testing protocol and written consent was obtained from each volunteer prior to participation. The injury risk associated with this study did not exceed the risk present during standard swim training sessions that these participants complete regularly (8 or more times a week). Participants were asked to refrain from resistance training 48 hours prior to testing in order to obtain maximal efforts without any influence of muscular fatigue. In addition, the following criteria were required of all volunteer participants: have no injuries, that caused removal from training or competition within the past 6 months, to the lower limb (i.e. hip, knee, foot, ankle, and all musculature involved) and be actively training and competing as a competitive swimmer. All participants in this study fulfilled these requirements.

6.1 Testing Protocol

Following a standard 1000m swimming warm up (similar to one performed at competition), each participant completed two submaximal practice starts and three maximal effort starts. The three maximal effort starts were recorded for the purpose of this study. Participants were given two minutes of rest between each trial to eliminate any influence of fatigue. From the three maximal effort dive starts completed, the fastest start (indicated by shortest predicted time to 2 meters) was used for further analysis.

6.2 Participant Performance Level

Participants were asked to report their top 3 events and best times for the 2013-2014 varsity season in order to quantify participant performance level. The corresponding FINA points were determined using the FINA Points Scoring 2013 table.

6.3 Leg Length and Foot Length

Although the scanogram x-ray technique has been considered the gold standard for leg length measurements, the tape measure method has shown strong reliability for leg length measurement (Beattie, Isaacson, Riddle, & Rothstein, 1990). Therefore, the leg length of each participant was recorded as the distance between the most inferior aspect of the anterior superior iliac spine and the medial malleolus of the ankle, of the right leg. Foot length was defined as measuring the distance between the most posterior aspect of the calcaneus and the most anterior aspect of the first metatarsal (i.e. heel to toe).

6.4 Navicular Drop

The navicular drop test was first described by Brody (1982). In the present study, we used a modified version of the navicular drop test as described by McPoil & Cornwall (1996). The protocol was completed by the same experienced physiotherapist for all participants. This test was used to determine the difference in height of the navicular tuberosity between neutral positioning and relaxed stance. Participants were asked to sit in a chair, with their knees flexed to 90˚, and the navicular tuberosity was marked. The height and drop of the navicular tuberosity in single leg stance has previously been used as an indicator of the magnitude of hind-foot eversion that is observed during rapid pronation (McPoil & Cornwall, 1996). Therefore, single leg stance was chosen to better evaluate the range of pronation that is experienced during dynamic function in a swim start. Participants stood on the foot that was identified as their preferred rear foot during the swimming block start, while flexing the knee of their other leg, placing them in a single leg stance. The talus was palpated and actively shifted to achieve sub-talar neutral positioning. In this neutral position, the height of the navicular tuberosity was marked on an index card that was placed perpendicular on the floor (Figure 9A). The participant then took five steps on the spot and returned to the same single leg stance, but this time in a relaxed position (Figure 9B). The height of the navicular tuberosity was marked on the same index card for this position. The difference of the navicular height between the neutral and relaxed position was recorded as the navicular drop (Figure 9C).

Figure 9: Navicular drop test- neutral positioning (A), relaxed stance (B), and navicular drop (C)

6.5 Kinetic Data Collection

A starting system (Daktronics, Inc., Brookings, SD, USA) was used to replicate competition starting conditions. Each start was performed on a replicated version of the Omega OSB11 swimming start block. This replicated block was equipped with two tri-axial force plates; one force plate (0R6-WP-2000 AMTI, Watertown, MA, USA) recorded the total forces applied to the block, and a second force plate (Omega 160, ATI, NC, USA) positioned below the rear foot rest recorded forces applied to the foot rest. The voltages from both force plates and the start signal were sampled using a 16-bit analog-to-digital conversion board (DAQPad-6015 National Instruments, Austin, TX, USA). These digital signals were then processed using a custom designed LabVIEW program (Version 10.0, National Instruments, Austin, TX, USA).

6.6 Kinematic Data Collection

The lower limb of each participant's preferred rear foot was marked using a grease marker (Eye Black EB1, Rawlings Sporting Goods Company, Inc.) to enable consistent measurements of the hind-foot eversion and dorsiflexing movements (McPoil & Cornwall, 1996) when the swimmer applied force to the block during the start. Laterally, the participant was marked at the head of the fifth metatarsal, the lateral malleolus, and the head of the fibula (Figure 10). Posteriorly, the participant was marked at the most prominent inferior bony aspect of the calcaneus, the most prominent superior bony aspect of the calcaneus at the insertion of the achilles tendon, the center of the achilles tendon at the height of the medial malleolus, and 15 cm above the previous marker in the middle of the leg (Figure 11; Stacoff, Kaelin, Stuessi, & Segesser, 1989). Two high-definition high-speed video cameras (EXILIM EX-FH20, Casio, Tokyo, Japan), with a resolution of 224 x 168 and a frame rate of 420 fps, were used to record lower limb movement during the block starts from lateral and posterior views. The video recordings were manually digitized using HuMAn (v5.0 HMA Technology, Guelph, Ontario, Canada) to quantify joint angles throughout the swimmer's movement on the starting block.

Figure 10: Lateral view markings of the rear foot on the starting block

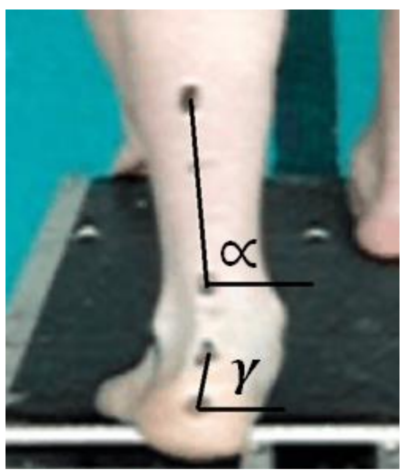

Figure 11: Posterior markings and hind-foot eversion angle; α represents the lower leg angle with respect to horizontal and γ represents the hind-foot angle with respect to horizontal

6.7 Data Analysis

6.7.1 Foot Measures

Navicular height is dependent on foot length; therefore, the navicular height in neutral and relaxed positions, as well as navicular drop, were normalized to foot length to result in better classification of foot type (Saltzman et al., 1995; D. Williams & McClay, 2000). This created three new measures for analysis: normalized navicular height in relaxed position, normalized navicular height in neutral position, and normalized navicular drop.

6.7.2 Kinetic Output Variables

Kinetic measures used for analysis included: block time (s) and kick plate time (s), defined as the total duration from the start signal to the participants last point of contact with the block and kick plate, respectively. Other measures included mass (kg), peak kick plate forces for anterior-posterior (A-P) and medial-lateral (M-L) directions, kick plate A-P impulse, and main plate A-P impulse. Specific performance measures included: take-off velocity (m/s) and a predicted time to 2 meters (s). Take-off velocity was calculated using the impulse-momentum relationship in the A-P direction (Equation 1), where t_i is the time of the start signal, t_f is the time of the last point of contact with the block, F_{AP} is the force in the A-P direction, and *m* is the swimmers body mass. A predicted time to 2 meters was calculated using a distance profile in the A-P direction (Equation 2), where the participant's center of mass at the start signal was located by calculating the whole-body center of pressure location with respect to the anterior edge of the starting block (d_i) and the participants A-P velocity was derived from the take-off velocity equation, *v(t).* Using the A-P distance profile, the time corresponding to the 2 meter distance determined the total time to 2 meters.

$$v(t) = \int_{t_i}^{t_f} \frac{F_{AP}}{m}\, dt \qquad \textbf{[1]}$$

$$\boldsymbol{d(t) = d_i + \int v(t)\, d(t)} \qquad \textbf{[2]}$$

An additional performance measure, normalized power (Equation 3), was calculated by normalizing each subject's average horizontal power (Equation 4) to their leg length (m) and mass (kg). Average horizontal power was calculated based on the rate of change of velocity in the A-P direction; based on the swimmers velocity at the start (V*i*) and the end of the block phase (V*f*), the swimmers mass (kg) and block time (s) (Bezodis et al., 2010).

$$\boldsymbol{P_N = \frac{P}{m \cdot g^{1/2} \cdot l^{3/2}}}$$ **[3]**

$$\boldsymbol{\overline{P} = \frac{m(V_f^2 - V_i^2)}{2 \cdot \Delta t}}$$ **[4]**

These kinetic output measures were used to develop additional measures:

1. Normalized peak A-P and M-L kick plate force was defined as the peak posterior and lateral forces applied to the kick plate. These output measures are represented as a percent of body weight and are important because they describe the magnitude and direction of force applied by the rear foot on the starting block (Arellano et al., 2005). Normalized peak A-P and M-L kick plate force equations are shown in equation 5 and equation 6, respectively; where the peak force (N) is normalized to the swimmers mass (N).

$$Peak\ f_{N(A-P)} = \frac{peak\ f_{A-P}}{m} \cdot 100\%$$ **[5]**

$$Peak\ f_{N(M-L)} = \frac{peak\ f_{M-L}}{m} \cdot 100\%$$ **[6]**

2. A ratio of kick plate impulse to total impulse (*kp:TotalImp*) described as the proportion of the total posterior impulse that was created by the rear foot (on the kick plate). The Kick Plate to Total Impulse Ratio is shown in equation [7]. This output measure is represented as a percent of the total impulse.

$$kpImp{:}TotalImp = \frac{KpImp}{TotalImp} \cdot 100\% \qquad \textbf{[7]}$$

6.7.3 Kinematic Output Variables

The output measures that were derived from kinematic data included: joint angle at set up, maximum angle achieved throughout movement, and change of angle (calculated from the difference between set up and maximum values). These measures were obtained for the hind-foot eversion and dorsiflexion angles, reflecting the movement of hind-foot with lower leg, and ankle joint, respectively. The hind-foot eversion angle is defined as the difference between the lower leg and the hind-foot angle, plus 180˚ to compensate for the right angles included in calculations of these angles (Refer to the hind-foot eversion angle in Equation 8 and corresponding Figure 11) (Stacoff et al., 1989). The hind-foot eversion and dorsiflexion angles were determined for each frame recorded.

$$\boldsymbol{Hind\ foot\ eversion\ angle = \propto - \gamma\ + 180^{\circ}} \qquad \textbf{[8]}$$

6.8 Statistical Analysis

Data for all participants tested was analyzed with independent t-tests to determine the statistical significance of differences between males and females in performance measures (predicted time to 2 meters, take-off velocity, normalized power, and block time) and foot anthropometrics (navicular drop and height, hind-foot eversion angles, and dorsiflexion angles). If the differences between males and females were statistically significant, then the remaining analyses would be performed separately for each sex.

Linear regression and Pearson product-moment correlation coefficients were then calculated to assess the relationship between the dependent variables. The level of significance was set at $p<0.05$ in all comparisons.

7 Results

The volunteer participants were comprised of provincial and national level competitive swimmers. Male and female participants had mean FINA point values of 691 (SD [min-max] =81[538-845]) and 693 (SD [min-max] =71[572-818]), respectively. The distributions of preferred rear foot and kick plate positioning for all participants are shown in Table 1. Most participants preferred to use the third or fourth kick plate setting and placed their left foot on the rear kick plate during their set up on the starting block.

Table 1: Number of participants, distributions of preferred rear foot and kick plate positioning

Rear Foot	Kick Plate Position					Total
Males (n=15)	#1	#2	#3	#4	#5	
Left	0	1	3	5	2	11
Right	0	0	0	4	0	4
Females (n=11)						
Left	0	1	7	0	0	8
Right	0	0	3	0	0	3
All Participants Total	*0*	*2*	*13*	*9*	*2*	*26*

There were no significant differences between sexes in normalized navicular drop, navicular height in neutral and relaxed stance, as well as set up, maximum, and change in hind-foot eversion and dorsiflexion angles during the kick start. Means, standard deviations, and ranges for male and female participants of start block kinematic values and foot anthropometric values are shown in Table 2.

Table 2: Foot Anthropometrics and Kinematic Values for Male and Female Participants, mean ± SD [min-max]

Foot Anthropometrics	Males (n=15)	Females (n=11)
Neutral WB navicular height (mm)	54.23 ± 5.64 [37-61]	48.45 ± 4.79 [42.56]
Relaxed WB navicular height (mm)	47.4 ± 6.59 [33-60]	42.36 ±6.6 [31-52]
Navicular drop (mm)	6.83 ± 5.19 [0-21]	6.09 ± 4.18 [0-14]
Normalized navicular drop (mm)	0.02 ±0.02 [0-0.07]	0.03 ± 0.02 [0-0.06]
Normalized navicular height (mm)	17.54 ± 2.79 [11.95-23.8]	17.48 ± 3.02 [13.3-22.3]
Kinematic Measures		
Dorsiflexion angle at set up (˚)	98.76 ± 11.19 [80.17-123.23]	98.07 ± 9.24 [86.75-118.29]
Max angle of dorsiflexion (˚)	92.49 ± 10.40 [78.12-119.65]	91.19 ± 10.34 [77.56-113.26]
Change in dorsiflexion angle (˚)	6.27 ± 3.07 [1.99-14.31]	6.88 ±3.41 [1.45-12.42]
Hind-foot eversion angle at set up (˚)	189.19 ± 7.95 [171.54-202.74]	183.88 ± 5.97 [172.7-192.82]
Maximum hind-foot eversion angle (˚)	192.93 ±7.97 [174.63-205.47]	187.55 ± 6.22 [174.56-197.05]
Change in hind-foot eversion angle (˚)	3.74 ± 1.89 [0.27-6.73]	3.68 ± 1.96 [1.2-7.53]

*significant differences between sex, p<0.05

During the kick start movement, the rear foot for both male and female participants was set up in an everted and slightly plantarflexed position. This everted positioning further increased from 189.2 degrees to 192.9 degrees for male participants and 183.8 degrees to 187.5 degrees for female participants. In addition, the maximum angles of dorsiflexion during the kick start were 92.5 degrees (males) and 91.2 degrees (females), indicating that the ankle is dorsiflexing when swimmers apply force to the kick plate. Furthermore, the mean proportion of total impulse that is created by the rear foot (placed on the kick plate) was 8.05% and 7.93% for male and female participants, respectively. Refer to Table 3 for the means, standard deviations, and ranges of block phase kinetic measures for male and female participants.

Table 3: Block Phase Kinetic Values for Male and Female Participants, mean ± SD [min-max]

Block Phase Kinetic Measures	Males (n=15)	Females (n=11)
Normalized Peak Lateral Kick Plate Force (%)	18.2 ± 8.1 [4.94-33.96]	10.8 ± 3.4 [4.6-16]
Normalized Peak Posterior Kick Plate Force (%)	116.65 ± 17.82 [92.36-154.58]	95.55 ± 9.79 [78.26-112.79]
Kick Plate Impulse to Total Impulse Ratio (%)	8.05 ± 0.89 [6.73-9.61]	7.93 ± 1.07 [6.27-9.91]
Kick Plate Time (s)	0.58 ± 0.04 [0.50-0.64]	0.60 ± 0.04 [0.53-0.68]

There were significant differences between sexes in all performance measures, including: predicted time to 2 meters, take-off velocity, normalized power, and block time ($p<0.05$).

The means, standard deviations, and ranges of performance measures for male and female participants are shown in Table 4.

Table 4: Performance Measure Values for Male and Female Participants, mean ± SD [min-max]

Performance Measures	Males (n=15)	Females (n=11)
Predicted time to 2 meters (s)	0.91 ± 0.03 [0.86-0.96]*	1.00 ± 0.04 [0.93-1.08]*
Normalized power	0.47 ± 0.04 [0.39-0.56]*	0.36 ± 0.05 [0.25-0.43]*
Block time (s)	0.68 ± 0.03 [0.63-0.73]*	0.76 ± 0.14 [0.60-1.16]*
Take-off velocity (m/s)	4.37 ± 0.13 [4.11-4.65]*	3.94 ± 0.22 [3.62-4.27]*

*significant differences between sex, p<0.05

7.1 Male Participants

The male participants had a strong positive relationship between the change of hind-foot eversion and normalized peak lateral kick plate force (r=0.47), as well as a moderate positive relationship between normalized navicular drop and normalized peak lateral kick plate force (r=0.39). The proportion of total posterior impulse that is produced by the kick plate impulse (Kick Plate to Total Impulse Ratio) is influenced by foot anthropometrics and rear foot joint angles; indicated by a moderate positive relationship with normalized navicular drop (r=0.38), a strong positive relationship to hind-foot eversion at set up (r=0.64), and a strong positive relationship to maximum hind-foot eversion (r=0.63). There was a strong negative relationship between neutral navicular height and change of dorsiflexion angle (r= -0.54), and a moderate negative relationship between neutral navicular height and change of hind-foot eversion angle (r= -0.45).

Start performance ability (defined by high normalized power, slow predicted time to 2 meters, and short block time) was significantly correlated to normalized peak posterior kick plate forces and kick plate time. Take-off-velocity, however, was not correlated to kick plate time and normalized peak posterior kick plate force. Hind-foot eversion set up and maximum joint angles positively influenced predicted time to 2 meters (r=0.44 and r=0.41, respectively) and negatively influenced normalized power (r= -0.43 and r= -0.40, respectively).There was a strong negative relationship between normalized peak posterior kick plate force and kick plate time (r= -0.75). There was a strong positive relationship between the Kick Plate to Total Impulse Ratio and predicted time to 2 meters (r=0.53).

The Kick Plate to Total Impulse Ratio was not strongly related to normalized kick plate peak posterior forces (r=0.18), and kick plate time (r=0.24).

Table 5: Kickplate Output Variables and Performance Measures for Male Participants, Pearson Correlations (r^2)

	Normalized Power	Predicted Time to 2m	Block Time	Take-Off Velocity
Kickplate Time (n=14)	-0.606 (0.367)*	0.753 (0.567)*	0.911 (0.829)*	-0.068 (0.005)
Normalized Peak A-P Kick Plate Force (n=15)	0.577 (0.333)*	-0.517 (0.267)*	-0.796 (0.633)*	-0.041 (0.002)

*indicates significant linear regression between measures, p<0.05

7.2 Female Participants

Similar to male participants, the female participants had a strong relationship between the change of hind-foot eversion and normalized peak lateral kick plate force (r=0.59), as well as a strong relationship between normalized navicular drop and normalized peak lateral kick plate force (r=0.40). The proportion of total posterior impulse that is produced by the kick plate impulse (Kick Plate to Total Impulse Ratio) is associated with rear foot joint angles; indicated by a moderate positive relationship to change in dorsiflexion angle (r=0.32), and a weak positive relationship to change in hind-foot eversion angle (r=0.23). There was a strong negative relationship between neutral navicular height and change of dorsiflexion angle (r= -0.64).

Hind-foot eversion set up and maximum joint angles positively influenced kick plate time (r=0.42 and r=0.42, respectively) and negatively influenced normalized peak posterior kick plate force (r= -0.44 and r= -0.30, respectively). Hind-foot eversion set up and maximum joint angles positively influenced predicted time to 2 meters (r=0.33 and r=0.38, respectively). In addition, normalized peak posterior kick plate force influenced performance measures, with a strong negative relationship to predicted time to 2 meters (r= -0.63), a moderate positive relationship to normalized power (r=0.32), and a weak positive relationship with take-off velocity (r=0.23). In addition, kick plate time influenced performance measures, with a strong positive relationship to predicted time to 2 meters (r=0.91) and block time (r=0.91), as well as a strong negative relationship to normalized power (r= -0.61). Similar to male participants, there was a strong negative relationship between normalized peak posterior kick plate force and kick plate time (r= -0.66). In addition, there was a strong positive relationship between this kick plate to total impulse ratio and kick plate time (r=0.61), and a weak negative relationship between the kick plate to total impulse ratio and peak posterior kick plate force (r= -0.23). As a consequence, there was a strong positive relationship between the kick plate to total impulse ratio and predicted time to 2 meters (r= 0.57).

Table 6: Kickplate Output Variables and Performance Measures for Female Participants, Pearson Correlations (r^2)

	Normalized Power	Predicted Time to 2m	Block Time	Take-Off Velocity
Kickplate Time (n=9)	-0.608 (0.369)*	0.906 (0.821)*	0.914 (0.836)*	-0.069 (0.005)
Normalized Peak A-P Kick Plate Force (n=11)	0.318 (0.101)	-0.632 (0.399)*	-0.296 (0.088)	0.226 (0.51)

*indicates significant linear regression between measures, p<0.05

8 Discussion

This investigation evaluates the performance implications of changing rear foot joint angles during the starting block phase of swimming competitions. The most significant aspects of this investigation were the quantification of hind-foot eversion during the start block movement and the implications between this movement and kick start performance.

The volunteer participants in this study were competitive swimmers with mean top FINA point values that are equivalent to Canadian Senior National time standards for 2013. This indicates that the participants in this study were experienced and nationally ranked competitive swimmers.

This study did not evaluate muscular contractions; however, the ankle angle was maintained and a posterior force was applied to the block through the fore-foot. This observation suggests that the plantarflexor muscles are active at this time and accordingly, that dorsiflexion movement during the early phase of the swimming start represents an eccentric contraction. If the plantarflexor muscles were not active, any forces created by the knee extensor muscles would cause complete (end-range) dorsiflexion of the ankle joint. Therefore, the relatively limited and controlled dorsiflexion movement that we observed in this study is assumed to be an eccentric contraction of the plantarflexors.

Kick start performance is influenced by rear foot movement of competitive swimmers on the Omega OSB11 block. Large hind-foot eversion movement is associated with high normalized peak lateral kick plate force. In addition, large hind-foot eversion movement, as well as dorsiflexion movement positively influences the contribution of the kick plate to total impulse. At first glance, an increased posterior impulse should contribute to improved performance; however, the start performance analysis indicated otherwise. Kick start performance is improved by high normalized peak posterior kick plate forces and short kick plate times. Accordingly, the posterior impulse is only one of the contributing factors. The data presented in this thesis illustrates that female swimmers who have high normalized peak posterior kick plate forces and short kick plate times also have reduced rear foot eversion joint angles on the starting block. In addition, these swimmers have larger contributions of the front leg and upper body to the total impulse. Consequently, this larger contribution to impulse from the front leg and upper body influences kick start performance through faster predicted time to 2 meters for both male and female swimmers, as well as higher normalized power for male swimmers. These individual factors and their contribution to kick start performance are discussed in the following sections.

8.1 Foot Anthropometrics

In the present study, the navicular drop test was recorded with participants in a weight bearing stance for all measurements; we observed mean values of 6.83 mm and 6.09 mm for male and female participants respectively, which are similar to findings of previous studies that evaluated the navicular height in dynamic activities. For example, previous evaluations of the navicular drop test during gait, where participants were weight-bearing for all measurements, report mean values of 6.49 mm (Griffin et al., 2013) and 5.3 mm (Nielsen, Rathleff, Simonsen, & Langberg, 2009). Although the limb positioning and amount of load are different in the current study compared to gait, the large forces during the kick start (116.5% body weight versus 95.5% for males and females respectively) appear to cause similar rear foot motion. In contrast, studies calculating the navicular drop as the difference between non-weight bearing neutral positioning and weight bearing relaxed stance report larger mean values compared to the dynamic method of navicular drop measurement: 7.13 mm (Eslami, Damavandi, & Ferber, 2013), 10.29 mm (Nam, Kwon, & Kwon, 2012), and 12.7 mm (Mulligan & Cook, 2013). Therefore, the weight bearing conditions of the navicular drop test used in the present study are different than the navicular drop test between non-weight bearing and weight bearing stance. The methods used for measuring foot anthropometrics and rear foot movement on the starting block were appropriate and reliable in order to collect accurate data throughout the kick start movement (Vinicombe et al., 2001) .

8.2 Ankle Dorsiflexion and Hind-Foot Eversion

The mean values for hind-foot eversion angles at set up were greater than 180 degrees for both male and female swimmers reflecting a pronated position at set up. As swimmers applied force throughout the kick start movement, their hind-foot further everted. The mean values for dorsiflexion angles reflected a plantarflexed position at set up for male and female swimmers (mean values of 98.8 degrees and 98.0 degrees, respectively). As swimmers applied force, the ankle dorsiflexed. This dorsiflexion movement is assumed to be an eccentric contraction of the plantarflexors that utilizes the elastic properties of the musculotendinous unit of the ankle plantarflexors to contribute to the subsequent concentric phase of the start block movement (Wilson & Lichtwark, 2011). Furthermore, we observed that a reduced eccentric contraction is associated with larger navicular heights. Reducing the extent of this eccentric contraction is faster because these swimmers apply posterior force to the kick plate through concentric plantarflexion movement without taking time in an eccentric contraction. This phenomenon was observed in a study investigating the performance impact of elite male swimmers between starting techniques with different stretch-shortening cycle properties, (with and without muscular pre-tension). They reported consistently better performances (defined by take-off velocity and block time) in concentric starts with pre-tension (Lee, Huang, & Lin, 2002). This study did not evaluate female swimmers; however similar findings would be expected. Therefore, swimmers (particularly those with low navicular heights) should apply muscular pre-tension to their rear foot during the block set up. This will reduce the eccentric phase of their plantarflexor muscles during the block start movement and contribute to improved start performance.

8.3 Normalized Peak Lateral Kick Plate Force

A swimmer applies force in the posterior direction throughout the entire block phase. Excessive motion in the medial-lateral (Caulfield & Garrett, 2004), as well as vertical (Slawson, Conway, Cossor, Chakravorti, & West, 2013) directions are considered inefficient. In the present study, male and female participants had a mean normalized peak lateral kick plate force value of 18.2% and 10.8% of body weight, respectively. Previous literature has discussed M-L forces during the start movement; however, the present study is the first to report specific values. Normalized navicular drop and hind-foot eversion movement is positively associated with normalized peak lateral kick plate forces for both the male and female swimmers; swimmers with larger normalized navicular drop and hind-foot eversion movement apply larger normalized peak lateral kick plate force. At first glance, force application in the lateral direction would not seem to lead to improved kick start performance; however, it may be that some lateral force is required to control rotational momentum (Hamill, Ricard, & Golden, 1986) during the kick start. In addition, lateral foot placement may also be related to lateral accelerations of the whole-body center of mass. For example, during the initiation of gait, M-L accelerations of the whole-body center of mass are strongly related to the lateral distance of the center of pressure (Donelan, Kram, & Kuo, 2001; Winter et al., 1998). When applying this concept to a swimming start, a swimmer applying large posterior forces with a wide stance (large lateral distance of center of pressure) will create large rotational momentum about their longitudinal axis (Hamill et al., 1986). However, lateral force applied to the kick plate may help by offsetting this angular momentum; this may help to maintain a direct anterior line of action throughout the kick start. This concept is supported by an investigation between narrow and wide foot stance during the kick start set up; swimmers who adopted a narrow stance had significantly better start performances (defined by take-off velocity, peak horizontal and vertical velocity, and block time; Slawson et al., 2013). Adopting a narrow stance could reduce the rotational momentum created by the wider stance and reduce the magnitude of lateral force that is necessary to maintain an anterior line of action. This allows the swimmer to apply larger force in the posterior direction and would explain the stronger start performances (Slawson et al., 2013).

8.4 Kick Plate Impulse to Total Impulse Ratio

The proportion of total impulse that is created by the kick plate was chosen as an appropriate measure to determine the influence of the rear foot (that is placed on the kick plate) to total momentum in the anterior direction. The majority of the posterior impulse during the block phase (approximately 92% for both male and female swimmers) is created by combined force application via musculature from the upper body and the front leg. Furthermore, the front foot remains in contact with the block for the entire block phase. Therefore, the front leg is expected to contribute the greatest amount to total posterior impulse. The present study indicated that foot anthropometric and kinematic measures (normalized navicular drop and hind-foot eversion movement) positively influence kinetic measures (Kick Plate to Total Impulse Ratio). Swimmers with larger normalized navicular drop and larger hind-foot eversion movement have larger contributions from the kick plate to total impulse. Furthermore, predicted time to 2 meters is positively influenced by this ratio (kick plate to total impulse); swimmers with less influence from the kick plate have a faster predicted time to 2 meters. An improved block start performance requires a larger influence of musculature from the front leg and upper limbs to the total impulse.

8.5 Normalized Peak Posterior Kick Plate Force and Kick Plate Time

Swimmers maintain a static stance prior to the start signal and must apply large amounts of posterior force for optimal starting efficiency. Despite similar mean values in kick plate time between male and female swimmers (0.58 seconds and 0.6 seconds, respectively), males applied greater normalized peak posterior force to the kick plate compared to females (116.5% body weight versus 95.5%, respectively). Male and female swimmers who achieved high normalized peak posterior kick plate force spent less time in contact with the kick plate. As the determinants of impulse, force and time play an important role in the output of predicted time to 2 meters. However, the swimmers who achieved high normalized peak posterior kick plate force with reduced contact time with the kick plate had a significantly faster predicted time to 2 meters and higher normalized power when leaving the block, as well as faster block times. These findings suggest that the swimmers who achieve shorter kick plate times compensate for the deficit in this impulse determinant by applying larger posterior forces to the kick plate and main plate. Therefore, these swimmers achieve an optimal magnitude of impulse (as observed in a fast predicted time to 2 meters) without spending any unnecessary time on the starting block.

8.6 Block Start Performance

Performance measures beyond water entry are greatly influenced by the swimmers ability in the underwater component (Cossor & Mason, 2001). Therefore, we have used performance measures from the starting block to isolate the contribution of the start itself.

8.6.1 Predicted Time to 2 Meters

Prior to the current study, this measure has been used in one swimming start performance research study (Murrell & Dragunas, 2012). This parameter is appropriate to evaluate a swimmers' performance in the block start because it evaluates a swimmers ability to propel their center of mass forward while considering their initial center of mass location and their anterior velocity. Furthermore, since the swimmers have not entered the water when their center of mass is 2 meters from the anterior edge of the starting block, this parameter evaluates their ability to leave the starting block before they contact the water (Murrell & Dragunas, 2012). In addition, predicted time to 2 meters is reported in seconds which is easily understood when providing feedback to swimmers, coaches, and other individuals involved. The predicted time to 2 meters for all swimmers ranged from 0.86 seconds to 1.08 seconds. For some swimmers, the best trial chosen for analysis was indicated by a faster predicted time to 2 meters by only one thousandth of a second. This small variability between kick start performances is consistent with a previous study that measured elite athlete track starts (Vantorre, Seifert, Fernandes, & Chollet, 2010). Multiple factors influence a swimmers start performance; accordingly, this study analyzed additional start performance measures in order to reliably determine the start performance implications of rear foot movement.

8.6.2 Normalized Power

In order to reliably evaluate start performance, normalized power was included to compliment the predicted time to 2 meters measure. As the integral of work with respect to time, a power output represents a swimmers ability to apply force to the starting block while considering the time required for them to complete the movement. Furthermore, a power value normalized to mass and leg length is appropriate for a start performance measure because individuals of different height and mass require different amounts of power to translate their center of mass forward (Bezodis et al., 2010; Moisio, Sumner, Shott, & Hurwitz, 2003).

Normalized power has been used in the running literature to evaluate block start performance (Bezodis et al., 2010). The mean normalized power value of male sprint runners was only slightly greater compared to male swimmers of the present study (0.51 and 0.47, respectively; Bezodis et al., 2010). The normalized power of female runners has not been reported in previous literature. Despite normalizing to body mass and leg length, this power measure still indicates sex differences in force and power output capabilities (Slawson et al., 2013); the normalized power measure of female swimmers in the present study were well below male runners and male swimmers (mean of 0.36).

Despite many differences between sprint running and swimming events, the demands of a block start are similar and require the athlete to apply large amounts of force as fast as possible, which is reflected in the power. Furthermore, male swimmers apply similar amounts of power to the starting block compared to male sprint runners. Swimming start block research can advance from information obtained from sprint running start block research (Mero & Komi, 1990; Slawinski et al., 2010; Slawinski, J. Bonnefoy, A. Leveque, J-M. Ontanon, G. Riquet, A. Dumas, R. Cheze, 2010).

8.6.3 Block Time

Block time is commonly used in swimming start performance literature and was included in the present study for comparison to previous research. In the present study, male and female swimmers had a mean block time of 0.68 seconds and 0.73 seconds, respectively. These block times were similar to times reported in previous studies evaluating the kick start on the Omega OSB-11 block (Barlow et al., 2014; Garcia-Hermoso et al., 2013; Honda et al., 2012; Ozeki et al., 2012; Takeda et al., 2012; Vint et al., 2008). In addition, the short block times of the present study supports the performance enhancing capability of the kick start on the OSB-11 starting block compared to the OSB-9 starting block, as well as the grab start technique. Block times on the OSB-9 starting block were slower with reported values between 0.77 and 0.89 seconds (Benjanuvatra et al., 2004; Blanksby, Nicholson, & Elliot, 2000; Mason, B. Alcock, A. Fowlie, 2002). Furthermore, block times reported with the grab start technique were even slower (0.94 seconds, Benjanuvatra et al., 2004; 0.95 seconds, Arellano, Llana, Tella, Morales, & Mercade, 2005).

Although block time has limitations as a performance measure for the swimming start, it has contributed valuable information when comparing results to previous literature. The mean block time of participants in the present study supports previous literature that evaluates the effect of the rear foot rest on the OSB-11 starting block to start performance. Furthermore, the block times indicate that the swimmers in the present study have similar performance levels compared to swimmers evaluated in previous literature.

8.6.4 Take-Off Velocity

Similar to block time, take-off velocity is a common measure used in block start performance literature despite the fact that recent investigations have identified limitations with using measures derived from impulse (Bezodis et al., 2010). However, due to the widespread use of take-off velocity in the past, it remains an important performance measure for comparative purposes. Male and female swimmers had significantly different mean take-off velocity values (4.37 m/s and 3.94 m/s, respectively). These results were similar to values reported in previous studies using the kick start technique (4.07 m/s, Vint et al., 2008; 4.41 m/s, Ozeki et al., 2012; 4.45 m/s and 4.55 m/s for front-weighted and rear-weighted starts, respectively, Honda et al., 2012; 4.53 m/s and 4.67 m/s for wide and narrow foot stance, respectively, Slawson et al., 2011).

9 Conclusion

Rear foot movement influences performance during the swimming kick start. Competitive swimmers with larger normalized navicular drop values and larger hind-foot eversion movement during the kick start have larger lateral kick plate forces, longer kick plate times, and larger contributions of the kick plate to total impulse. These swimmers also have larger eccentric contractions of the rear foot plantarflexors during the block start. Improved start performance is associated with applying high normalized peak posterior kick plate force as quickly as possible while using the front leg as the dominant contributor to total impulse. A swimmer achieving these start movement characteristics have faster predicted time to 2 meters, higher normalized power at block exit, as well as faster block times.

10 Practical Applications

A successful swimming start performance consists of a fast block exit while also contributing to overall race performance through high velocity and appropriate body position at water entry (Vantorre et al., 2010). Previous research has primarily evaluated the influence of hip and knee joint angles (Slawson et al., 2012), center of mass location (Barlow et al., 2014), and kick plate setting during block set up (Takeda et al., 2012). However, many factors contribute to the swimming start performance; the present study describes the performance implications of rear foot movement. This study determined that swimmers with large hind-foot eversion and dorsiflexion movement in the kick start can improve their start performance by reducing hind-foot eversion during set up on the block. In addition, gait research suggests that individuals can reduce their M-L forces by adopting a narrower stance (Donelan et al., 2001; Winter et al., 1998) which may be directly applicable to the swim start too. Furthermore, swimmers could apply pre-tension to their lower limb musculature prior to the start movement to reduce the dorsiflexion movement and contribute to faster onset of the plantarflexion movement.

Swimmers should also learn to apply higher posteriorly directed force via the front leg which is the greatest contributor to impulse. Swimmers that apply high normalized peak kick plate posterior forces as fast as possible (large power) accelerate their center of mass forward at a greater rate.

Furthermore, swimmers with large hind-foot eversion movement and/or with a large navicular drop can potentially use training programs to target muscular deficits and improve control of hind-foot eversion and dorsiflexion throughout the kick start movement. Therefore, competitive swimmers may be able to limit hind-foot eversion movement and position themselves effectively on the starting block in order to improve performance in the swimming kick start.

10.1 Limitations

The findings of the present study reflect a specific population of competitive swimmers. The volunteer participants were all swimmers on the same nationally ranked team with similar training and experience with the swimming kick start on the Omega OSB11 block. Therefore, the present study may not be directly relevant for different starting technique and experience levels or with different models of starting blocks. However, given the growing evidence of the superiority of the kick start and the universal adoption of the Omega OSB-11 block at international swim competitions, this may not represent a severe limitation. Participants were highly encouraged to complete the dive testing protocol with maximal effort; however, effort is subjective and there are currently no appropriate measures for quantifying effort during this type of exertion. The high degree of reproducibility of the repeated dives in this protocol indicates that the swimmers' efforts were consistent. In addition, the fact that the diving performance measures were comparable with previously published findings on elite swimmers indicates that the swimmers' efforts were maximal.

The navicular drop test protocol was completed by an experienced physiotherapist with extensive knowledge of foot anatomy; however, the measurements were only collected once, and they were all collected by the same individual. Repeated testing on different days was not completed, but this may have further improved reliability of the data collected. If we had employed multiple assessors then we would have been able to examine the inter-rater reliability of these measures, and also been able to evaluate whether our results with one rater may be generalizable to other raters.

10.2 Considerations for Future Experiments

The present study has described rear foot movement during the kick start performance. Future studies should investigate the performance implications of rear foot movement while measuring center of pressure location and stance width. This would enable a more comprehensive assessment of the angular momentum during the swim start which may have implications for subsequent parts of the swim start, such as the entry phase (Vantorre et al., 2010). Additional force data should also be collected to distinguish between the specific contributions of the front leg and upper limbs to the total impulse.

A muscle training program focusing on the intrinsic foot muscles performed for three minutes each day significantly reduced participants navicular drop from 12.7 mm at baseline compared to 10.9 mm and 10.5 mm at 4 and 8 weeks of intervention, respectively (Mulligan & Cook, 2013). This training program targets muscular deficits (particularly the abductor hallucis), teaches effective muscular recruitment, and prevents excessive lowering of the medial longitudinal arch. This training adaptation in navicular drop indicates that an individual’s intrinsic muscles may be capable of adapting to training interventions. Competitive swimmers may potentially improve their dynamic control of pronation and support of the medial aspect of the foot by increasing strength of the plantarflexor and invertor muscles, specifically medial soleus, flexor digitorum longus, flexor hallucis longus, and tibialis posterior. In addition to their main function of plantarflexing and inverting the foot, these muscles often act eccentrically to resist dorsiflexion and eversion movements. Future investigations should evaluate muscular training interventions and their ability to increase a swimmers dynamic ability on land, including the swimming kick start.

Given that we have identified the influence of rear foot movement on swim start performance, and the fact that it can be altered with training (Mulligan & Cook, 2013), we believe that it should be incorporated into future tests. Furthermore, since the foot is so heavily loaded during the starts, we suggest that the navicular drop test should be performed under weight-bearing conditions, as performed in this thesis. A weight bearing stance places the plantar fascia and bony arches of the foot under load. This loading lowers the initial height of the navicular tuberosity when it is measured in a neutral position. Therefore, lower navicular drop test values are expected when a dynamic and weight bearing method of testing is used. This dynamic method of navicular drop testing is appropriate to reflect sub-talar joint motion during dynamic function and should be further evaluated for use in dynamic investigations.

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Appendices

Appendix A: Literature evaluating swimming start performance, in chronological order

Authors (year)	Starting Block	Start position(s)	Sample Size	Population Specifics	Output Measures *(main performance measure)*	Concluding Notes
Guimaraes & Hay (1985)	Slanted	Grab	24	Highschool level	*Time to 9m* Block time Flight time Horizontal and vertical center of mass displacement Average horizontal and vertical velocity Height of center of mass at take-off and entry Horizontal impulse Time that the feet contact water Time that the hands contact water	Time to 9m is associated with horizontal velocity from feet, and horizontal and vertical velocity from hands.
Schnabel & Kuchler (1998)	Slanted	Unspecified	Unspecified	German National Swimmers	*Time to 15m* Block time Flight time Underwater time Transition time Horizontal velocity	Time to 15m is strongly influenced by horizontal velocity, water resistance, and velocity at 7.5-15m. Efficiency and ability to transition between phases are important to start performance.
Mason & Cossor (1999)	Slanted	Unspecified	Unspecified	1999 Pan-Pacific Championships	*Time to 15m*	Time to 15m significantly predicted outcomes in all races.
Arellano, Pardillo, De La Fuente, & Garcia (2000)	Slanted	Unspecified	17	National Level	*Time to 5m & 10m* Flight time Horizontal and vertical take-off velocity Horizontal and vertical entry velocity Take-off angle Mean velocity between 0-5m Peak horizontal and vertical force	Despite these measures, the problem of start performance was attributed to the transfer of horizontal velocity from the flight phase to the underwater glide phase.
Blanksby, Nicholson, & Elliott (2000)	Slanted	Grab Track Handle	12	National level (5 Males, 7	*Time to 10m* Reaction time Block time Movement time Flight time and distance Center of mass at set-up	Regular practice improves start performance, irrespective of technique.

Appendix A continued:

Authors (year)	Starting Block	Start position(s)	Sample Size	Population Specifics	Output Measures *(main performance measure)*	Concluding Notes
Cossor & Mason (2001)	Slanted	Unspecified	Unspecified	Finalists and Semi-finalists at the Sydney 2000 Olympic Games	*Time to 15m* Block time Flight time Flight distance Underwater time & distance	Underwater phases significantly predicts time to 15m.
Holthe & McLean (2001)	Slanted	Grab Track	10	Male, Collegiate level swimmers	Flight distance Speed at take-off and entry Angle at take-off and entry Height of center of mass at take-off and entry	Track start: improved flight distance by 10cm, entry speed by 0.3-0.4m/s, had higher center of mass at take-off, and lower center of mass at entry.
Lee, Huang, Lin, & Lee (2002)	Slanted	Grab	8	swimmers	Block time Flight time and distance Peak horizontal and vertical velocities Vertical and horizontal take-off velocities Vertical and horizontal entry velocities	Muscular pre-tension indicates shorter block times and larger horizontal take-off velocities when compared to a stretch-shortening cycle strategy.
Breed & Young (2003)	Slanted	Grab Rear-weighted Track Swing	23	Female, non‑competitive swimmers	Take-off velocity Take-off angle Horizontal and vertical impulse Flight time and distance Entry angle	Resistance training improved take-off velocity, take-off angle, and horizontal impulse of rear-weighted track starts.
Benjanuvatra, Lyttle, Blanksby, & Larkin (2004)	Slanted	Grab Track	16	National level (9 Males, 7	*Time to 6m* Reaction time Movement time Block time Velocity of center of gravity at take-off Peak horizontal and vertical force Average horizontal and vertical force Horizontal and vertical impulse	Track Start: Faster movement time and block time, increased average horizontal force. Different force profiles between front and rear foot dominance.
Arellano, Llana, Tella, Morales, & Mercade (2005)	Slanted	Grab	11	University, State, National level (6 Males, 5 Females)	*Time to 5m, 7.5m, & 10m* Time hands leave block Block time Time the hands meet water & time the feet meets water Mean velocity during 0-5m, 5-7.5m, and 7.5-10m Peak horizontal and vertical force Horizontal and vertical take-off velocity Angle at take-off Horizontal and vertical force relative to body-weight	Horizontal force is significantly related to 5m time and mean horizontal velocity during 0-5m phase.
Chen & Tang (2005)	Slanted	Grab Track	8	Competitive (4 Males, 4	Flight distance Peak horizontal and vertical force Horizontal impulse Entry angle	Start performance is associated with combining horizontal velocity, flight distance, and entry angle. Authors note the importance of combined efficiency in all measures.

Appendix A continued:

Authors (year)	Starting Block	Start position(s)	Sample Size	Population Specifics	Output Measures *(main performance measure)*	Concluding Notes
Benjanuvatra, Edmunds, & Blanksby (2007)	Slanted	Grab	16	9 Elite level 7 Recreational level	*Time to 5m and 15m* Reaction time Movement time Block time Horizontal and vertical impulse Take off velocity Take off angle	Elite swimmers have faster time to 5m, 15m, and larger horizontal impulse. Take-off velocities were similar between groups.
Mason, Alcock, & Fowlie (2007)	Slanted	Grab Track	6	Elite level	*Time to 5m & 10m* Movement time Block time Peak horizontal force Take-off angle Horizontal take-off velocity Average acceleration at take-off Average power Peak power	Peak power (normalised to body mass), average power, and peak horizontal force are significantly related to time to 5m and 15m.
Ruschel, Araujo, Pereira, & Roesler (2007)	Slanted	Unspecified	4	National and State level	*Time to 15m* Block time Flight time and distance Angle of entry Maximum depth achieved Underwater phase distance and time Average velocity-underwater phase	Flight distance, angle of entry, maximum depth achieved, and average velocity of the underwater phase are significantly correlated with time to 15m.
Galbraith, Scurr, Hencken, Wood, & Graham-Smith (2008)	Slanted	Track Modified 1-hand Track	12	National level (5 Males, 7 Females)	*Time to 10m* Block time Flight time and distance Total time (block time + flight time) Peak horizontal and vertical force Horizontal take-off velocity	Track starts had faster time to 10m compared to the modified one-hand track start. Peak horizontal force, take-off velocity, block time, and flight time are significantly related to time to 10m.
Welcher, Hinrich, & George (2008)	Slanted	Grab Track (front vs rear weighted)	20	National level, Females	*Time to 5m and 7.5m* Block time Time hands meet water Horizontal velocity at take-off and 5m	Front-weighted starts have faster block time. Rear-weighted starts have greater horizontal velocity. At time to 5m, front-weighted lost advantage to rear-weighted starts. Rear-weighted starts had greater instantaneous horizontal velocity at 5m and better combined time and velocity than front-weighted at 5m.
Bishop, Smith, Smith, & Rigby	Slanted	Unspecified	22	Competitive	*Time to 5.5m* Distance and time to head contact with water Take-off angle Entry angle Take-off velocity	Take-off velocity and distance to head contact was related to time to 5.5m.

Appendix A continued:

Authors (year)	Starting Block	Start position(s)	Sample Size	Population Specifics	Output Measures *(main performance measure)*	Concluding Notes
Hardt, Benjanuvatra, & Blanksby (2009)	Slanted	Track	22	Age group (11 Males, 11 Females)	*Time to 5m*	Footedness and dominant limb are independent of performance and preferred stance on the starting block. Preferred stance is significantly related to Time to 5m.
Takeda, Ichikawa, Takagi, & Tsubakimoto (2009)	Unspecified	Unspecified	10	Male, University	Horizontal velocity	There were significantly different velocities during the initial start and transition phases between maximumal starts, sub-maximal starts, and maximal wall push offs. Velocity differences were eliminated during the stroke phase.
Vint, Hinrichs, Riewald, Mason, & McLean (2009)	Slanted, with and without rear foot-rest	Kick Grab (front & side grip)	50	Junior elite (30 Males, 20 Females)	*Time to 6m* Block time Horizontal and vertical Impulse horizontal and vertical take-off velocity Peak horizontal power (normalized to body weight) Take-off angle Velocity at 6m	The rear footrest increased horizontal take-off velocity and peak horizontal power, and reduced block time.
Burkett, Mellifont, & Mason (2010)	Slanted	Grab Track	20	Olympic and Paralympic	*Time to 15m* Block time Flight time and distance Underwater time, distance, & velocity	Authors note importance of increased underwater velocity and optimal transition time for improved free swimming velocity.
Seifert, Vantorre, Lemaitre, Chullet, Tousaint, & Vilas-Boas (2010)	Slanted	Grab	11	Male, Elite Sprinters	*Time to 15m* Block time Flight time and distance Angle at take-off and entry Velocity at entry	Different take-off 'styles' result in similar time to 15m. Authors note importance of generating large take-off velocities as quickly as possible to optimize start performance.
Vantorre, Fernandes, Vilas-Boas, & Chollet	Slanted	Grab Track	7	Elite, Male freestyle specialists	*Time to 15m* Block Time Flight Time Reaction Time Number of underwater kicks Horizontal and vertical impulse	No differences between the time to 15m of track and grab starts due to influence of underwater phase.
West, Owen, Cunningham, Cook, & Kilduff (2011)	Slanted	Unspecified	11	Male, International Sprinters	*Time to 15m* Peak horizontal and vertical force Rate of force development	Rate of force development is moderately associated to time to 15m.
Slawson, Conway, Cossor, Chakravorti, Le-Sage, & West (2011)	Omega OSB-11	Kick	33	Elite British (17 Males, 15 Females)	Block time Peak horizontal force Peak fertical Force Peak horizontal force from kickplate Peak vertical force from kickplate Horizontal take-off velocity Head distance at entry	Using kick plate position 4 and 5, narrow stance, and right foot forward was associated with larger peak horizontal and vertical forces and larger take-off velocity.

Appendix A continued:

Authors (year)	Starting Block	Start position(s)	Sample Size	Population Specifics	Output Measures *(main performance measure)*	Concluding Notes
Honda, Sinclair, Mason, & Pease (2012)	Omega OSB-11	Kick	18	Elite Australian (9 Male, 9 Female)	*Time to 5m and 7.5m* Reaction time Block time Take-off horizontal velocity Average velocity between 5m and 7.5m Average horizontal Force Peak kick plate resultant force Peak kickplate horizontal and vertical force Peak vertical grab force	Using a kick plate setting that is one position back from preferred resulted in greater flight distance, horizontal velocity, and faster time to 5m. There were no performance differences between kick plate positions at time to 7.5m.
Ozeki, Sakurai, Taguchi, & Takise (2012)	Slanted (with or without rear footrest)	Track Kick	11	Elite, Male, Collegiate Level	*Time to 15m* Block time Horizontal and vertical take-off velocity Speed at take-off Flight distance Entry angle	The kick start had faster block time, faster time to 15m, increased horizontal take-off velocity, and increased speed.
Slawson, Chakravorti, Conway, Cossor, & West (2012)	Omega OSB-11	Kick	10	National level, Male Sprinters	Horizontal take-off velocity Block time (main plate and foot rest) Reaction time Peak horizontal force (main plate and foot rest) Peak vertical force (main plate and foot rest)	Foot rest positioning did not change knee joint angles. Peak horizontal force occurs between rear knee angle of 100-110˚.
Takeda, Takagi, Tsubakimoto (2012)	Slanted, with adjustable kick plate	Kick	10	Male, Collegiate	*Time to 5m* Horizontal and vertical take-off velocity Resultant take-off velocity Block time Horizontal velocity at 5m Flight distance Take-off angle Kick plate time	There were no significant differences in performance measures between changes to kick plate set up.
Garcia-Hermoso, Escalante, Arellano, Navarro, Dominguez, &	Slanted, Omega OSB-11	Grab Track Kick	1657	Elite International and National level	*Block time*	When using a slanted block, the block time was significantly associated with performance, whereas the block time of the OSB-11 block is only associated with Women's 50m Free time.
Barlow, Halaki, Stuelcken, Greene, & Sinclair (2014)	Omega OSB-11	Kick (front, neutral, rear-weighted)	10	National sprinters (7 Males, 3 Females)	*Time to 5m & 15m* Reaction time Block time Movement time Take off angle Entry angle Mean velocity at 4.5-5.5m & 14.5-15.5m	Rear-weighted starts had longer block times. However, neutral and rear-weighted starts had faster 5m & 15m times compared to front-weighted starts.

Appendix B: Ethics Approval Notice from the Research Ethics Board at the University of Western Ontario

Western Research

Research Ethics

Use of Human Participants - Initial Ethics Approval Notice

Principal Investigator: Dr. Jim Dickey
File Number:104843
Review Level: Delegated
Protocol Title: The effect of rear-foot rigidity on the swimming start performance
Department & Institution: Health Sciences\Kinesiology,Western University
Sponsor:
Ethics Approval Date: February 11, 2014 **Expiry Date:**April 30, 2014
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Other	Study data collection form to record pronation of participant from navicular drop test	2013/12/18
Other	Study data collection form to record participant competition level and block set-up preferences	2013/12/18
Western University Protocol	Ethics Protocol v2.0 clean copy pdf	2014/01/21
Letter of Information & Consent	Revised LOI and Consent form. Clean copy PDF. Version 3.0.	2014/01/21

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

[redacted]

Signature

Ethics Officer to Contact for Further Information

[redacted]

This is an official document. Please retain the original in your files.

[redacted]

Curriculum Vitae

Name:	Amber Hutchinson
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Related Work Experience	Teaching Assistant The University of Western Ontario 2012-2014