When observing an athletic sprint start using starting blocks, it is common to see high performing athletes twist their lower bodies followed by their legs flailing out sideways. Despite limited scientific information on 3D pelvis and leg motion in sprinting, some coaches believe that performance would improve if the athletes tried to curtail limb motion outside the sagittal plane. This thesis has tried to shed light on this movement pattern and to see how manipulating 1st step width affects force production and performance.

By measuring the 3D full-body motion of competitive sprinters, it was found that step width was not related to performance but to how much the athletes were pushing sideways and how much they were lifting the pelvis on the side of swing leg. By using a complex musculoskeletal model to estimate how much the leg muscles were propelling the athletes, it was found that narrowing step width reduced the ability of the leg muscles to generate force and decreased performance. Whole-body and segment angular momentum were also examined to aid our understanding of why segment motion occurs outside the sagittal plane. The results from that study suggested that coordinated segment motion could assist the sprinters by preventing the large pushing forces from making them rotate away from the finish line. In conclusion, the idea that this twisting and flailing action is likely to be detrimental to performance was not supported by this thesis.

Paul Sandamas

After his bachelor studies Paul worked as a full-time tennis coach in London. A passion to optimise his players’ techniques and improve coach education led to an interest in biomechanics and an MSc in Biology of Physical Activity at the University of Jyväskylä, Finland. His Master’s thesis focused on 3D inverse dynamics of the lower body in the tennis forehand.
ATHLETIC SPRINT START BIOMECHANICS
Athletic Sprint Start Biomechanics
Investigations into the relationships between three dimensional starting technique, first step width and performance
Paul Nicolas Sandamas
To Sari and our daughters, Inari and Aurora
Abstract

The block and early acceleration phase plays a very important role in the overall outcome of athletic sprint events. During this part of the race it is commonly observed that sprinters use a lower-body technique that involves the swing leg crossing medially in front of the athlete followed by wide steps. These wide initial steps give the impression that the legs are flailing out to the side. Some coaches believe that this action could be inefficient and thus should be curtailed. However, there is limited knowledge about this movement pattern and its relation to performance.

Therefore, the overall aim of this thesis was to help elucidate from a biomechanical perspective a) the fundamental underlying kinematic and mechanical basis to this technique and b) how both performance and muscular contributions to propulsion would be affected when step width was restricted.

A cross sectional study design was used to examine specific kinematic and kinetic variables from 11 competitive sprinters (9 male, 2 female) performing maximum effort 15 m sprint starts. Three-dimensional kinematics, ground reaction force and electromyographical data were recorded from the block phase to the end of the 1st stance phase. Each athlete performed five trials with their natural technique and five trials inside a 0.3 m wide lane. A 15-segment, full-body model and a 37 degrees of freedom full-body musculoskeletal model were created and used to calculate relevant variables/parameters. Normalised average horizontal external power was used as the performance measure.

A combination of pelvis list and rotation (but not hip adduction) was found to be coupled with the thigh of the swing leg moving medially during the single push phase. In the unrestricted width trials, pelvic list range of motion and medial impulses correlated positively with step width but step width was not found to be related to performance. When step width was restricted, a more forward pointing normalised average ground reaction force vector was seen but lower body muscular contributions to acceleration were reduced and no immediate improvement to performance was found.

The primary kinematic reason behind the lower body posture the sprinters adopt during the block phase whereby the swing leg moves medially in front of the body is caused by
a combination of three dimensional pelvis rotations rather than simply hip internal rotation/or adduction of the swing leg. Trying to reduce pelvic range of motion or minimising the flailing leg motion is unlikely to lead to an improvement in performance. Therefore, the notion that this technique is inefficient, was not supported by this study.

List of scientific papers

This thesis is based on the following papers referred to by their Roman numerals:


II. Martín de Azcárate, L., Sandamas, P., Arndt, A., Gutierrez-Farewik, E. M., & Wang, R. The effect of step width on muscle contributions to body mass center acceleration during the first stance of sprinting (Submitted).


IV. Sandamas, P., Gutierrez-Farewik, E. M., & Arndt, A. Angular momentum and external torque during the block and 1st stance phase of the sprint start (Submitted).
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### Abbreviations and variables

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<thead>
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<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>BW</td>
<td>Body weight</td>
</tr>
<tr>
<td>CFSQP</td>
<td>C functions of sequential quadratic programming</td>
</tr>
<tr>
<td>CoM</td>
<td>Centre of mass</td>
</tr>
<tr>
<td>CoP</td>
<td>Centre of pressure</td>
</tr>
<tr>
<td>DP</td>
<td>Double push</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyography</td>
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<tr>
<td>GCS</td>
<td>Global coordinate system</td>
</tr>
<tr>
<td>GRF</td>
<td>Ground reaction force</td>
</tr>
<tr>
<td>GRFv</td>
<td>Ground reaction force vector</td>
</tr>
<tr>
<td>IAA</td>
<td>Induced acceleration analysis</td>
</tr>
<tr>
<td>JCS</td>
<td>Joint coordinate system</td>
</tr>
<tr>
<td>LCS</td>
<td>Local coordinate system</td>
</tr>
<tr>
<td>Norm</td>
<td>Normalised</td>
</tr>
<tr>
<td>PB</td>
<td>Personal best</td>
</tr>
<tr>
<td>QTM</td>
<td>Qualisys track manager</td>
</tr>
<tr>
<td>RoM</td>
<td>Range of motion</td>
</tr>
<tr>
<td>SP</td>
<td>Single push</td>
</tr>
<tr>
<td>SW</td>
<td>Step width</td>
</tr>
</tbody>
</table>

- $\vec{\mathbf{H}}$: Angular momentum
- $\vec{\tau}$: Torque
- $F_{\text{GR,front}}$: The angle between the vertical and mediolateral components of the GRF
- $F_{\text{GR,sag}}$: The angle between the anteroposterior and vertical components of the GRF
- $F_{\text{GR,trans}}$: The angle between the anteroposterior and mediolateral components of the GRF
- $H_x$: Anteroposterior component of angular momentum
- $H_y$: Vertical component of angular momentum
1 Introduction

Top-level sprinting is a sport with global appeal. The 2012 Olympic 100 m final was broadcasted to 220 countries with an estimated television audience of 20 million in the UK (IOC, 2012) and 2 billion worldwide (Stanley, 2012). The 100 m is one of the blue-ribbon events at the Olympic Games and the 100 m world record holder is often described in the media as the “fastest man on Earth”.

The block and first stance phases represent the greatest and second greatest change in anteroposterior velocity (and hence correspondingly, the two greatest net anteroposterior impulses) of any part of the race (Nagahara, Kanehisa, & Fukunaga, 2020). World class sprinters can reach top speeds of approximately 12 m/s and leave the starting blocks at approximately 3.5 m/s which suggests that an athlete’s push phase contributes to approximately 1/3 of the maximum speed (Taylor & Beneke 2012; Willwacher et al., 2013). The importance of a good start to overall performance is emphasised by the strong correlations between both block exit and 1st stance velocity, and 100 m race time (Mero 1988).

During of the block and early acceleration phases of sprinting it is commonly observed that athletes adopt a lower body technique that to the casual observer might look inefficient. From the block to mid-flight phase this technique primarily involves a combination of rear (swing) side upward pelvic list and rear side forward pelvic rotation with rear side hip flexion (Debaere et al., 2013) (Figure 1a). This action is mirrored for the front (swing) leg during 1st stance (Figure 1b). This 3D pelvic and swing leg motion appear to give wide step widths at the beginning of the race and a flailing action of the legs (Ito, Ishikawa, Isolehto, & Komi, 2006; Jessop, 2011). As the sprinter progresses into a more upright posture, the range of pelvic list, rotation, hip abduction and hence, step width reduces and becomes consistent for the remainder of the race (Nagahara et al., 2017; Ito et al., 2006). This lower body technique resembles to some degree, (at least to the author), the lower body technique used for forward propulsion in ice skating, and was therefore, called “skating style” in Paper I. The inclusion criterion for this study and our definition of “skating style” for Paper I was that the participant’s mean 1st step width was at least 30% greater than the step width of their trials performed inside a narrowed (0.3 m wide) track.
Some high performance coaches believe that high amounts of frontal and transverse plane range of motion (RoM) are detrimental to performance and pelvic motion and initial step width should be reduced. Although there has been a great deal of research in sprinting, most studies have only focused on sagittal plane motion during the start phase. This means that there is a complete dearth of information on the skating technique, and until this PhD commenced, no study had been performed to describe this technique. Therefore, this thesis is focused on investigating this skating technique and its relationship with performance.

2 Background

2.1 Definition of terms

As this thesis has focused on the block start technique from the “set” position to the end of the first stance phase, the specific definitions of the start phases, sub-phases and their respective key events are given in Figure 2.

![Figure 2](image)

Figure 2. Definition of the phases, sub-phases and their associated key events of the sprint start. Modified from Bezodis, Willwacher, & Salo (2019).

2.2 Quantifying performance

The ultimate way of measuring performance during a race is finishing time. However, measuring performance over a single part of the sprint presents more of a challenge. Is it better to account for the time taken to reach a specific distance (such as 5 or 10 m), the anterior velocity of an athlete at that distance or anterior velocity at a specific event e.g.
block exit or first step toe-off? These are several of the measures that have been used in the sprint literature (e.g. Baumann, 1976; Mero & Komi, 1990; Mero, Luhtanen, & Komi 1983; Mero et al., 2006). The problem arises when different and possibly conflicting conclusions are reached depending on what measure of performance is used (Bezodis, Salo & Trewartha 2010).

In order to determine what could be the most appropriate measure of performance Bezodis et al. (2010) compared ten measures of performance for a group of 12 sprinters. The performance measures were: anterior block exit velocity, average anterior block phase acceleration, average anterior external block power, as well as time to, and velocity at, 10, 20 and 30 m. Not surprisingly none of the performance measures ranked the sprinters in the same order. This suggests that investigators should be clear about what their measure of performance is actually quantifying.

Prior to the study by Bezodis et al. (2010), the most common way of measuring block performance was anterior block exit velocity (Bezodis et al., 2019). Anterior block exit velocity is related to anterior impulse, and impulse is combination of both anterior force and time. This means that the same block exit velocity could be produced with a low average force acting over a long time or a high average force acting over a short time. Increasing pushing time goes against the nature of sprinting which is to cover a certain distance in the shortest possible time (Bezodis et al., 2010). To overcome this limitation, Bezodis et al. (2010) proposed average external power (\(P_{\text{AEL}}\)). Average external power is calculated by dividing the change in kinetic energy by the pushing time and hence takes into consideration both change in velocity and time. Average external power can then be normalised by taking into account the mass and leg length of the athlete to give normalised average external power (\(P_{\text{NAEL}}\)). Normalised average external power is now a commonly used measure of performance for the sprint start as well as the early and mid-acceleration phases (Bezodis et al., 2019).

### 2.3 The Block Phase

#### 2.3.1 Sprint start positioning

As previously discussed from a kinetic point of view the goal of the block start is to maximise \(P_{\text{NAEL}}\). However, the sprinter must continue to accelerate efficiently throughout the rest of the acceleration phase and so an additional goal of the block start involves setting up the athlete “in the proper sprinting form” (Helmick, 2003). According to the rules set out by World Athletics (formerly IAAF), the athletes can alter the distance of the foot plates from the starting line and the inclination (obliquity) of the foot plates (World Athletics, 2019).

#### 2.3.1.1 Foot plate spacing

Based on the anteroposterior spacing between the front and rear foot plates, three types of start position are commonly described. These are bunched (typically \(< 0.3\) m), medium (between \(0.3\) and \(0.5\) m) and elongated (\(> 0.5\) m) (Harland & Steele, 1997). The consensus is that the bunched start allows for a shorter block pushing time whereas the elongated start leads to greater block exit velocity due to longer pushing time (Dickinson, 1934; Henry, 1952; Slawinski et al., 2012). However the disadvantages of the bunched position is that it reduces the extension capabilities of the hips and front knee and therefore provides the least opportunity to develop force (Henry, 1952). The longer pushing time of the elongated start is also not recommended as it was found to lead to longer times at the 5 and 10 m mark compared to the bunched and medium start positions (Slawinski et al., 2012). The medium block spacing is therefore recommended as it allows for a powerful start without excessive pushing time (Harland & Steele, 1997; Bezodis et al., 2019).

#### 2.3.1.2 Foot plate inclination

Three studies have analysed the effect of foot plate inclination on performance. Guissard, Duchateau & Hainaut (1992) compared footplate angles of \(70°\), \(50°\) and \(30°\), while Mero et al. (2006) compared footplate angles of \(40°\) and \(65°\). Both studies utilized a within-sprinter approach and concluded that the anterior centre of mass (CoM) velocity at block exit was greatest with the smallest footplate inclination without a statistically significant concomitant increase in the pushing time. Mero et al. (2006) confirmed the theories of Guissard et al. (1992) by concluding that the greater block exit velocities with the smallest footplate inclination were due to increases in ankle joint moments and power, which in turn were caused by the elongated muscle tendon length of the triceps surae and greater utilisation of the stretch shortening cycle (SSC). However the cross-sectional study by Schrödter, Brüggemann & Willwacher (2017) did not find a relationship between athletes’ natural block obliquity and \(P_{\text{NAEL}}\). Bezodis et al. (2019) suggested that the contrast between the studies could be partly explained by the difference between a within-athlete and cross-sectional study and by differences in the footplate surface lengths used.

#### 2.3.1.3 Mediolateral foot placement on the starting blocks and performance

A couple of studies have investigated the effect of manipulating the starting block medialateral foot placement and performance. Henson, Cooper & Parry (2002) compared 1st step width and mean time to 5, 10, 15 and 30 m using starting block “toe-to-toe”
foot width spacings of 0.24 m (conventional), 0.38 m (intermediate) and 0.52 m (lateral). Although the mean times to 5, 10 and 30 m were a few 1/100 s lower with the intermediate block spacing, they were not statistically significant different from the other spacings. Despite these non-significant results, the authors argued that since small time differences can affect the outcome of a race, the intermediate spacing could enhance performance compared to the conventional spacing. From a methodological point of view, it is unclear between which toes “toe-to-toe width” was measured in this study. Furthermore, additional statistical tests, such as effect size, could have been performed to assess the practical significance of the results.

Otsuka et al. (2015) also investigated the effect of stance width at the “set” position and performance by comparing lateral foot spacings of 0.25 ± 0.01 m (normal) and 0.45 ± 0.02 m (widened). Stance width was calculated from the mediolateral distance between the midpoints of the 1st and 5th metatarsals. The rationale for this study was as follows:

- The greatest power of any joint during the block phase is found in the hip joints (Bezodis et al., 2015).
- Hip extension in the block phase is similar to the barbell squat exercise.
- Stronger lower limb isometric contractions have been found during squatting when the stance width is increased (Demura et al., 2010).
- During the barbell squat an enhanced mean gluteus maximus muscle activity is found during a widened stance (McCaw et al., 1999).

They therefore hypothesized that a widened stance width during the block start would increase hip joint power and block performance ($P_{NAH}$).

Compared to the normal condition, the hip joint abduction angles were greater throughout the block phase, and more internally rotated during the double push (DP) phase, for both legs in the widened condition. Although the peak value of rear hip power was greater in the widened condition, no significant benefit to performance, or time to 2 m, was found (Otsuka et al., 2015).

Otsuka et al. (2015) also commented that when comparing their results to the literature, larger changes in performance can be made in changing block inclination angles (Mero et al., 2006) or anteroposterior block distance (Slawinski et al., 2010) than by changing mediolateral foot placement. Although World Athletics does not specify what block width spacings can be used in competition, the athletes must use the starting blocks provided by the race organizer. And since no manufacturer currently makes width-adjustable starting blocks, Bezodis et al. (2019) commented that there is “limited need” for more research on this topic as allowing the sprinters to adjust their foot width does not appear to enhance performance.

2.3.1.4 Mediolateral foot placement on the starting blocks and step width

Parry, Henson, & Cooper, (2003) used the same data from the study by Henson et al. (2002) to investigate stance width at the “set” position and 1st step width. Their results are presented graphically in Figure 3. The average deviations of the rear foot from a straight line in the anterior direction were; 8.7 cm laterally for the conventional stance width, 0.02 cm medially for the intermediate and 1.65 cm medially for the widest (lateral) stance width.

The authors’ claimed that this was evidence that the standard starting blocks are too narrow and they cause the athlete to place the rear foot out to the side in order to maintain balance which in turn slows down the athlete. Although this sounds reasonable these findings should be interpreted with caution. Firstly, athletes who started with the right foot in front on the starting block were not included in this analysis, and so it is unclear how many data points were collected. Secondly, no standard deviations were reported so it is impossible to assess the variability in the data. And thirdly, since no statistical difference (or other statistical methods e.g. effect size) testing was performed, there is no way of knowing how statistically significant the results of this study are.

Figure 3 An illustration of the mean 1st stance foot placement in the anterior and mediolateral directions with respect to the corresponding starting position. The numbers; 1, 2 & 3 refer to the mediolateral foot spacing on the starting blocks i.e. 1 - conventional, 2 - intermediate and 3 - lateral. The base of each arrow represents the rear (right) foot’s location on the starting blocks and the filled squares represents the corresponding location of the rear foot at 1st stance touchdown. Modified from Parry et al. (2003).
2.3.1.5 Joint angles at the “set” position and performance
Several studies have focused on the relationship between sagittal plane lower body joint angles in the “set” position and a) block exit velocity (Coh et al., 1998; Mero et al., 1983) and b) $\text{P}_{\text{PAM}}$ (Bezodis et al., 2015). Since only weak correlations and wide inter-participant variation were found, the results of these studies suggest that a range of “set” positions can be used and hence there is no single optimal “set” position.

2.3.2 Block Phase Kinematics

2.3.2.1 Lower body kinematics
On reacting to the starting command both hips and knees extend while the ankles initially dorsiflex and then plantarflex until block exit (Charalambous et al., 2012; Brazil et al., 2017). During the single push (SP) phase the hip and knee joint of the rear leg start to flex. The rear knee stops flexing at approximately block exit whereas the rear hip stops flexing during the flight phase (Debaere et al., 2013). The hip, knee and ankle of the front leg continue to extend during SP phase, reaching their maximum extension angles during the flight phase.

Although the vast majority of studies of the sprint start have focused on the sagittal plane motion, a few studies have illustrated the whole-body three dimensional nature of the sprint start (Debaere et al., 2013; Slawinski et al., 2010). The data from Debaere et al. (2013) illustrated the motion of the pelvis (with respect to the global frame) and lower limbs (with respect to the pelvis segment) in all three planes. During the block phase, the pelvis undergoes retroversion tilt in the sagittal plane and rearside upward tilt in the frontal plane. Whereas, in the transverse plane, the pelvis rotates towards the front side during the double push (DP) phase followed by rear side rotation during the SP phase (Debaere et al., 2013). This pelvis motion is coupled with changes in the hip joint angles. During the SP phase, the hip joint of the front leg not only extends but also abducts and internally rotates. In comparison, the hip joint of the rear leg flexes, with a slight external rotation (≈5°) and virtually no abduction or adduction (Debaere et al., 2013).

The order in which the joints of the front leg reach their peak angular velocities is similar to that seen in explosive extension tasks, i.e. a proximal-to-distal sequence (Brazil et al., 2017; Slawinski et al., 2010; Bobbert et al., 1988). In contrast, for the rear leg, the knee reaches peak angular velocity first, followed by the hip and then ankle (Bezodis et al., 2015; Brazil et al., 2017).

2.3.2.2 Upper body kinematics
Despite high level coaches describing the importance of arm motion to sprint performance (Jones et al., 2009) there is a paucity of data on upper body motion during the sprint start. Slawinski et al. (2010) illustrated the 3D angular velocities of the shoulder and elbow joints as a function of time. From this the asymmetrical nature of the movements of both arms can be quantified. Although it is easy to observe the rear shoulder extending and the front shoulder flexing during the SP and flight phases, during the DP phase both shoulders extend while the torso rises. While both shoulders are extending, the peak rear shoulder angular velocity (≈700 °/s) is more than double that of the front shoulder angular velocity (≈250 °/s). During the SP phase the front shoulder changes direction in the sagittal plane to flexion, reaching a peak flexion angular velocity of approximately 200 °/s (Slawinski et al., 2010). Both shoulders reach peak abduction and external rotation angular velocities during the SP phase. Front shoulder peak abduction and external rotation angular velocities are similar to peak front shoulder flexion angular velocity (≈200 °/s). In contrast the rear shoulder peak abduction and external rotation angular velocities are different. Peak abduction and external rotation angular velocities were approximately 150 °/s and approximately 350 °/s, respectively during the SP phase. The authors (Slawinski et al., 2010) also found more variation in arm than leg kinematics between sprinters.

Bhowmick & Bhattacharayya (1988) have suggested that the role of the arms in the sprint start are; to regulate leg movement, to aid a forceful leg drive and to balance the angular momentum produced by the lower body. Although these views were generally supported by the elite sprint coaches interviewed by Jones et al. (2009) no direct evidence exists to substantiate these claims for the sprint start.

2.3.3 Block Phase Kinetics

2.3.3.1 Orientation of the GRF vector
Otsuka et al. (2014) compared the orientation of the average resultant GRF vector in the sagittal and transverse planes between groups of well-trained, trained and non-trained sprinters. They found the average sagittal plane GRF vector was pointed further forward in the well-trained group. Whereas in the transverse plane, the average resultant GRF vector pointed more anteriorly for the non-trained compared to the trained group. Although several studies have reported the 3D block forces as a function of time, there is very little information regarding the direction of the GRF vector with respect to the CoM of the sprinter. This is useful when considering the external torques applied to a body and the corresponding changes in angular momentum. Payne & Blader (1971) illustrated the direction of the resultant sagittal plane GRF with respect to the CoM...
during the block phase. They showed that the resultant GRF vector points forward below the CoM during the DP phase and then forwards above the CoM during the terminal part of SP phase. Payne & Blader (1971) described how the GRF vector pointing forward below the CoM would tend to rotate the body anticlockwise (when viewed from the right side of the athlete), while a GRF vector pointing forward above the CoM would tend to rotate the athlete in the opposite direction. They also assumed that a similar pattern would be seen during the following “several steps” as the athlete straightens up out of the crouched position.

2.3.3.2 Impulses

Studies in the 1970’s and 1980’s showed that higher performing sprinters produce greater anterior net impulses, anterior peak and average forces and block power than sprinters of lower ability level (Baumann, 1976; Mero et al, 1983). In addition to peak force, the rate of force development has also been found to be greater in elite sprinters compared to well-trained sprinters (Slawinski et al., 2010; Coh et al., 2017).

When the individual forces from each footplate have been measured, the results have shown the front leg produces 66-76% of the total anterior impulse because it is in contact with the starting blocks 1.9 to 2.4 times longer than the rear foot (Guissard & Duchateau, 1990; Coh et al., 2009; Bezodis et al., 2015). Despite this, some studies have shown larger peak anterior forces from the rear leg (compared to the front leg) and that force magnitudes from the rear leg are indicators of performance (when measured as $P_{N AH}$) (Fortier et al., 2005; Guissard & Duchateau, 1990; Willwacher et al., 2016; Bezodis et al., 2019). Furthermore, during the DP phase the rear leg contributes more to the anterior and vertical components than the front leg (Coh et al., 2017; Otsuka et al., 2014).

2.4 First Stance Phase

Although the greatest change in anterior velocity is seen during the block phase, the greatest change in anterior velocity whilst solely in contact with the track is seen during the 1st stance phase (Salo, Kerinen & Viitasalo, 2005). The demands of maintaining balance after the flight phase, maximising anterior acceleration and rising from a crouched position has led to the first stance phase to be called the “most difficult stride in the entire sprint race” (Mann, 2013).

2.4.1 Kinematics

2.4.1.1 Touchdown distance

The first two steps after block exit are the only steps during which the foot is planted posterior to the CoM i.e., a negative touchdown (TD) distance (Coh & Tomazin, 2006; Mero et al., 1992). The mean first stance TD distance was found to be - 0.131 ± 0.057 m in the study by Mero et al. (1983). A more negative TD distance is associated with a more forward leaning position and the ability to generate greater anterior GRFs (Kugler & Janshen, 2010). However, the computer simulation study by Bezodis et al. (2015) found an inverted-U shaped relationship between TD distance and first stance $P_{N AH}$ suggesting an optimal TD distance is likely to exist beyond which performance will decrease.

2.4.1.2 Lower body kinematics

The ankle joint of the stance leg dorsiflexes during the initial 40% of stance and then plantar flexes for the remainder (Debaere et al., 2013; Brazil et al., 2017). In contrast, the knee and hip joints of the stance leg only extend during stance. The peak angular velocities of the stance leg joints follow a proximal-to-distal sequence (Brazil et al., 2017). This proximal-to-distal sequence of peak angular velocities concurs with the extension-rotation model of Jacobs & van Ingen Schenau (1992). In order to optimise motion in the anterior direction, the knee and ankle joints would need to delay extension until the hip has translated over the initial point of contact with the ground due to anatomical and geometric constraints (Jacobs & van Ingen Schenau, 1992).

Although there is limited information regarding 3D joint kinematics, Slawinski et al., (2013) and Debaere et al., (2013) have highlighted that during the 1st stance phase maximum hip angular velocity is reached with a combination of hip flexion-extension, abduction-adduction and internal-external rotation.

2.4.1.3 Step Width

Ito et al. (2006) was one of first to provide empirical evidence on step width during high level competition. They showed that the initial steps after leaving the starting blocks are wider than when the athlete is running at top speed. Data were obtained from sprinters competing in the 2005 World Championships in Athletics. For a group of 18 International level sprinters, step width between the first and second stance averaged 0.39 ± 0.07 m compared to 0.17 ± 0.04 m when running at top speed (Ito et al., 2006). This observation has been recently corroborated by Nagahara et al. (2017) who reported the average step width over four steps (e.g. steps 1-4 and 5-8 etc.) from the start to the 52 m mark. The results by Nagahara et al. (2017) illustrated how step width decreased rapidly...
from the 1st to the 13th step and remained close to an average of \(0.09 \pm 0.05\) m thereafter.

### 2.4.1.4 Step width and performance level

The study by Ito et al. (2006) also compared step width and performance level. Based on their finishing times in the recorded 100 m race, the 18 sprinters were divided into two groups of nine. No statistical differences were found for step width between the groups. A study by Otsuka et al. (2014) provided data on step width for the front foot to first step and first to second step between groups of well-trained, trained and non-trained sprinters. No significant differences between skill level and step width were found in this study. The average step width for the 1st to 2nd step was \(0.31 \pm 0.08\) m for the well-trained sprinters which is narrower than the \(0.39 \pm 0.07\) m 1st to 2nd step width reported by Ito et al. (2006). This could be due to several reasons, including differences in participant stature and measurement techniques. The study by Ito et al. (2006) did not provide participant stature information and they measured step width from images recorded from a video camera (image frequency unknown) positioned in the spectator tribune of the stadium.

### 2.4.2 Kinetics

#### 2.4.2.1 External kinetics

First stance anteroposterior ground reaction forces consist of an initial braking phase followed by a much longer propulsive phase (approximately 87-92% of total stance time) (Bezodis et al., 2020; Mero, 1988). The net anteroposterior impulse typically increase a sprinters’ anterior velocity by around \(1.20\) m/s (Debaere et al., 2013; Mero, 1988) and greater net anteroposterior impulses are associated with higher level sprinters (Slawinski et al., 2010). Although it is tempting to imagine that higher performing sprinters generate less braking impulses, this has not been shown (Morin et al., 2015). Furthermore, it would also be expected that TD distances show some relationship to braking impulses (i.e. a more negative TD distance the less the braking impulse). However, even though this is generally true, the study by Bezodis et al. (2014) showed that even with a relatively large negative TD distance athletes can still produce braking impulses.

#### 2.4.2.2 Use of musculoskeletal models to investigate lower body joint and muscle contributions to CoM acceleration during the sprint start

Debaere et al. (2015) performed a muscle-driven induced acceleration analysis (IAA) to estimate the contributions made by the lower-body joints and muscles to wholebody CoM propulsion and lift during the first two stances in sprinting. They reported that the ankle joint contributes the most to propulsion and lift during both stances compared to the knee and hip joints. At a muscular level, the plantar flexors (soleus and gastrocnemius) contribute the most to propulsion and lift.

The relatively low contribution by the hip to propulsion reported by Debaere et al. (2015) appears to differ from previous research that has highlighted the importance hip extension to anterior CoM acceleration, particularly during the initial part of stance (Johnson & Buckley, 2001; Jacobs & van Ingen Schenau 1992). Inverse dynamics studies have shown that a proximal-to-distal pattern is found for peak stance leg joint power, as well as peak joint angular velocities and resultant joint moments (Brazil et al., 2017).

Since the study by Debaere et al. (2015) only reported the net contributions for whole stance phase, the temporal changes during the stance phase have been omitted. An alternative use of the IAA method involves calculating the contributions of muscle forces to the GRF vector thereby showing how the muscles contribute to propulsion and lift throughout the stance phase e.g. Hamner et al. (2010).
3 Aim

The overall aim of this thesis was to attempt to understand the biomechanical aspects of segment motion outside the sagittal plane during the sprint start and its relationship with performance.

The specific aims were:

1. To investigate if a reduction in 1st step width would cause a more anteriorly pointing average force vector which could lead to an improvement in block and 1st stance net anterior impulses (Paper I).
2. To investigate how muscle contributions to propulsion and support would be influenced when the 1st step width was restricted (Paper II).
3. To describe the kinematics underlying the phenomenon of the knee of the swing leg passing medially in front of the athlete and determine the relationships between block phase pelvis RoM, 1st step width and performance (Paper III).
4. To investigate whole-body angular momentum, external torque and the contributions of segment groups to angular momentum to further understand the reasons why segment motions occur outside the sagittal plane (Paper IV).
4 Methods

4.1 Summary of the data collection

Competitive sprinters performed 10 maximum effort block starts in the biomechanics laboratory at GIH. Marker derived kinematics, ground reaction force (GRF) and electromyographic (EMG) data were collected from the start to the end of the 1st stance. Five starts were recorded with the athlete performing his/her natural technique and five trials were performed with the athlete sprinting inside a 0.30 m wide lane. The trials with the 0.30 m lane required each sprinter to perform with a reduced step width and were the “narrow” trials analysed in Papers I and II. One data collection was performed to obtain all the raw data for this PhD.

4.1.1 Participants

Eleven competitive sprinters volunteered to participate in the data collection. A summary of the number of participants for each study and their mean age, mass and personal best are given in Table 1. Anthropometric data (height and weight) were measured for each participant. Height was measured on a wall mounted stadiometer and weight was recorded from a force plate (Kistler 9281EA). Each participant was informed of the methods of the study and signed an informed consent form. The experimental procedures of this study were approved by the Stockholm Regional Ethical Committee.
Table 1. Characteristics of the participants included in the thesis.

<table>
<thead>
<tr>
<th>Study</th>
<th>Number (gender)</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>100m Personal best (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>10 (8M, 2F)</td>
<td>23.9 ± 6.3</td>
<td>1.79 ± 0.09</td>
<td>72.7 ± 13.6</td>
<td>11.03 ± 0.36 &amp; 11.30</td>
</tr>
<tr>
<td>II.</td>
<td>4 (2M, 2F)</td>
<td>24.5 ± 7.2</td>
<td>1.75 ± 0.10</td>
<td>70.3 ± 14.0</td>
<td>11.14 ± 0.23 &amp; 11.30</td>
</tr>
<tr>
<td>III.</td>
<td>11 (9M, 2F)</td>
<td>23.8 ± 5.3</td>
<td>1.77 ± 0.10</td>
<td>72.7 ± 13.3</td>
<td>11.02 ± 0.34 &amp; 11.30</td>
</tr>
<tr>
<td>IV.</td>
<td>9 (8M, 1F)</td>
<td>24.9 ± 5.4</td>
<td>1.81 ± 0.08</td>
<td>75.8 ± 12.5</td>
<td>11.03 ± 0.36 &amp; 11.30</td>
</tr>
</tbody>
</table>

4.1.2 Participant preparation

After an individualised warm up, 78, 12.5 mm passive reflective markers (Figure 4) and 12 pairs of EMG surface electrodes were attached to each athlete prior to motion capture. The Ag/AgCl surface electrodes (Ambu A/S, Denmark) (inter-electrode distance 2 cm) were placed bilaterally on the muscle bellies of the: gluteus maximus, gluteus medius, biceps femoris-long head, vastus lateralis, gastrocnemius medialis and soleus muscles. Skin preparation and electrode placement were in accordance with the recommendations given by SENIAM  (http://seniam.org). The reference electrode was attached to the tibial tuberosity of the right leg. All EMG electrode wires were secured to the athlete with tape. EMG data were recorded at 1500 Hz using a telemetered system (Noraxon TeleMyo 2400T G2, Noraxon USA Inc., Scottsdale, USA.) with the transmitter unit securely attached to the thoracic spine using a custom-made backpack. Due to the time required to prepare the athlete, the athletes performed a second (shorter duration) warm up prior to data capture.

Figure 4. Location of the 78 passive reflective markers. The marker locations were: left and right fore- and rear-head, left and right acromion, clavicle, sternum, C7, L1, medial and lateral elbow, medial and lateral wrist, 2nd and 5th metacarpal heads of both hands, anterior superior iliac spine, iliac crest, posterior superior iliac spine, medial and lateral knee, medial and lateral ankle, calcaneus, 1st and 5th metatarsal heads, and head of the first toe. Eight technical clusters were strapped to the mid-humeri, mid-radius, mid-femur and mid-shank. The medial ankle and knee markers were removed after the static calibration pose was recorded. The participant gave consent for the use of this image.

4.1.3 Laboratory setup and procedures

Testing took place indoors in a laboratory fitted with a 1.22 m wide tartan running surface. The running track was 15 m long, fitted with a crash mat on the end wall. The athletes were given several warm up trials to familiarise themselves with the data collection procedures. Kinematic data were recorded at 250 Hz using a 12 camera (Oqus 4, Qualisys AB, Göteborg, Sweden), three dimensional motion capture system (Figure 5). Four of the cameras were tripod mounted at approximately 1.3 m above the ground, positioned to reduce marker occlusion during the crouched position. The remaining eight cameras were wall mounted (2.90 m above the ground). The motion capture system was calibrated for each session according to the manufacturer’s guidelines using a 0.60 m calibration wand (Qualisys, 2011). The mean standard deviation of the wand length was 1.17 ± 0.17 mm. Kinetic data were recorded at 1500 Hz from single force transducers beneath each footplate of the starting block (Kistler 9347B, Winterthur,
Switzerland) and from a force plate (Kistler 9281EA), recording the first step GRFs. The kinematic, kinetic and EMG data were collected simultaneously in Qualisys Track Manager (QTM, Qualisys AB). The athletes were allowed to adjust the starting blocks to their own preferred block spacing and block obliquity. The position of the starting blocks was adjusted in the anteroposterior and mediolateral directions during the warm up trials to ensure foot contact was made inside the force plate load cell boundaries. Five trials were performed with the athlete performing his/her natural technique and five trials were performed with the athlete running inside a 0.30 m lane, which corresponds to the width between the starting blocks. The narrow lane was constructed by laying two parallel ropes on the track surface. The ends of each rope were attached to the outside edges of the starting blocks and terminated at the crash mat. The athletes were given as many trials as they thought necessary to familiarise themselves with the demands of a narrow start. The athletes used the same block spacing and block obliquity for the natural and narrow trials. Data collection was performed outside the competitive seasons.

Figure 5. Plan view of the data collection setup. The origin of the global coordinate system (GCS) and its orientation is also shown.

4.1.4 Starting blocks

Custom-made instrumented starting blocks were used to accurately determine the key events of: movement onset, rear block exit and front block exit. A single force transducer (Kistler 9347B) was screwed to each footplate and a custom-made steel plate screwed to the surface of the transducer (Figure 6). As the sprinters wore spiked shoes, an offcut from the running surface material was cut to match the size of the custom-made footplate and attached with heavy duty carpet tape. Subsequent references to front and rear legs refers to the leg’s position on the starting blocks.
A standing reference trial was recorded for each participant in order to create a personalised mathematical model. The mass of each segment was determined from total body mass using regression equations (Dempster, 1955). The Hanavan mathematical model was used to determine both the location of each segment’s the CoM and each segment’s principal moments of inertia based on the marker locations (Hanavan, 1964). The knee and ankle joint centres were defined as the midpoint of the femoral epicondyles and malleoli, respectively. The pelvis segment was the Visual 3D coda pelvis. The hip joint centre was defined according to Bell, Brand & Pedersen (1989). A local coordinate system (LCS) was created for each model segment as follows: first, an anatomical plane was created between the markers defining the segment’s proximal and distal joints, the y axis was defined along the distal to proximal end of the anatomical plane (i.e. the longitudinal axis of a segment). Second, the x axis was at 90° to the y axis and the frontal plane of the segment, and third, the z axis was the cross product of the x and y axes according to the right hand rule. Segment parameters (mass, location of each segment’s CoM and moment of inertia) and each segment’s LCS were computed automatically during model creation in Visual3D. As the majority of the participants started with their left foot on the front block, data from the contralateral athletes were inverted.

4.1.6 Data filtering
Starting block transducer voltages were filtered at 50 Hz and kinematic data were filtered at 12 Hz, using a 4th order, low pass, Butterworth filter. Filtering frequencies were chosen from Fourier and residual analyses (Winter, 2005). The force plate data were unfiltered.

4.1.7 Event creation
The key events and how they were defined in Visual3D are shown in Table 2.

<table>
<thead>
<tr>
<th>Event</th>
<th>Definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start (i.e. movement onset)</td>
<td>The first instance when the 1st derivative of either the front or rear block resultant force-time curve was &gt; 500 N/s.</td>
<td>Brazil et al. (2017)</td>
</tr>
<tr>
<td>Rear block exit</td>
<td>The first frame the rear block resultant force dropped below 0 N.</td>
<td></td>
</tr>
<tr>
<td>Block exit</td>
<td>The first frame the front block resultant force dropped below 0 N.</td>
<td></td>
</tr>
<tr>
<td>First stance touchdown</td>
<td>The first frame the Vertical GRF was &gt; 10 N.</td>
<td>Rabita et al. (2015)</td>
</tr>
<tr>
<td>First stance toe-off</td>
<td>The first frame the Vertical GRF was &lt; 10 N.</td>
<td>Rabita et al. (2015)</td>
</tr>
</tbody>
</table>

4.2 Study design and variables analysed
A summary of the study design and analysed variables is shown in Table 3.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Study design</th>
<th>Phase(s)</th>
<th>Analysed variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Comparison between Skating and Narrow</td>
<td>Block and 1st stance</td>
<td>CoM motion, step width, ( P_{\text{NAHB}} ), ( P_{\text{NAH}} ), GRF angle, impulse, GRFs</td>
</tr>
<tr>
<td>II.</td>
<td>Comparison between Skating and Narrow</td>
<td>1st stance</td>
<td>Lower body muscle contributions to CoM acceleration, step width, GRFs</td>
</tr>
<tr>
<td>III.</td>
<td>Natural trials</td>
<td>Block and 1st stance</td>
<td>Pelvis segment angles and hip joint angles Step width, ( P_{\text{NAHB}} ), ( P_{\text{NAH}} ), Whole-body and segment angular momentum, external torque</td>
</tr>
<tr>
<td>IV.</td>
<td>Natural trials</td>
<td>Block and 1st stance</td>
<td></td>
</tr>
</tbody>
</table>
4.2.1 Step width and step length (Papers I - IV)
Step width and step length were calculated from the mediolateral and anteroposterior distances, respectively, between the midpoints of the 1st and 5th metatarsal head markers of the leading foot on the starting block to the rear foot at first touchdown (Otsuka et al., 2014). Step width and step length were normalised and made dimensionless by dividing by leg length (vertical coordinate of the hip joint centre, computed during the standing reference trial).

4.2.2 Definition of narrow, natural and skating trials (Papers I - IV).
Narrow refers to all trials performed inside the narrowed (0.3 m wide) track, whereas natural refers to all unrestricted step width trials. Skating style was defined as the trials when the 1st step width that was at least 30% greater than the step width of the athlete’s narrow trials.

4.2.3 Centre of mass (CoM) motion (Papers I - IV)
The position of the whole-body CoM with respect to the GCS was calculated using the following equation:

$$\text{CoM} = \frac{1}{M} \sum_{i=1}^{15} m_i \vec{r}_i$$

(1)

where $M$ is the total mass of the athlete, $m_i$ is the mass of a segment and $\vec{r}_i$ is the position vector of the $i$ segment CoM with respect to the origin of the GCS.

4.2.4 CoM velocity (Papers I - IV)
CoM velocity was calculated using the First Derivative function in Visual3D. Since the motion is recorded in discrete time steps, the central difference method is used to calculate velocity from the coordinates of the whole-body CoM. The equation used is:

$$v_i = \frac{s_{i+1} - s_{i-1}}{2\Delta t}$$

(2)

where $v_i$ is the velocity at time $i$, $\Delta t$ is the time interval (1/250 s) and $s$ is the linear position of the CoM.

4.2.5 Normalised average horizontal power (Papers I - IV)
Normalised average horizontal power ($P_{NAH}$) was used as the measure of performance. The method was based on the equations given by Bezodis et al. (2010). Average horizontal power ($P_{AH}$) was calculated from:

$$P_{AH} = \frac{m(v_{final} - v_{initial})^2}{2\Delta t}$$

(3)

where $m$ = subject mass, $v_{final}$ = anteroposterior CoM velocity at end of 1st stance phase, $v_{initial}$ = anteroposterior CoM velocity at start of 1st contact phase, $\Delta t$ is the 1st stance contact time. Average horizontal block power ($P_{AHB}$) was computed using equation 3, but using initial and final CoM velocities of the block phase ($v_{initial} = 0$ at start of block phase), and $\Delta t$ is the block pushing time.

The $P_{AH}$ and $P_{AHB}$ were normalised and made dimensionless:

$$P_{NAH} = \frac{P_{AH}}{m \cdot g^{3/2} \cdot l^{1/2}}$$

(4)

where $g$ is the acceleration due to gravity and $l$ is the leg length (vertical coordinate of the hip joint centre, computed during the standing reference trial). Normalised average horizontal block power ($P_{NAHB}$) was computed similarly to using equation 4, but with the $P_{AHB}$ as the numerator.

Normalised average horizontal block power ($P_{NAHB}$) was used to determine each athlete’s “best” trial for analysis in Papers III and IV.

4.2.6 Relative impulse (Paper I)
The impulse-momentum relationship illustrates the relationship between the change in the momentum of a body by a force acting over a period of time (i.e. an impulse). The impulse-momentum relationship is derived from Newton’s second law and can be expressed as:

$$\int_{t_{initial}}^{t_{final}} \vec{F} \, dt = m\vec{v}_{final} - m\vec{v}_{initial}$$

(5)
where \( \vec{F} \) is the ground reaction force, \( m \) is the mass of the athlete and \( \vec{v} \) is the velocity of the CoM.

Net impulses were calculated from the force plate data by numerically integrating (trapezium rule) the area under the force-time graph from time \( t_{\text{initial}} \) to \( t_{\text{final}} \). To obtain the net impulse in the vertical direction the body weight impulse was subtracted from the vertical impulse. By dividing the net impulse by the athlete’s mass, the change in velocity (m/s) during the ground contact phase was obtained. This was expressed as the relative impulse (Hunter et al., 2005).

4.2.7 Projection angles (Paper I)
The ensemble average of both the magnitude and direction of the GRF vector during ground contact was used to give a visual representation of the external forces generated between the skating and narrow trials. The GRF vectors projected onto the sagittal (x-y), frontal (z-y) and transverse (x-z) planes were calculated in degrees as follows:

\[
F_{\text{GR sag}} = \tan^{-1} \left( \frac{\text{mean vertical GRF}}{\text{mean anteroposterior GRF}} \right) \cdot \frac{180^\circ}{\pi}
\]

\[
F_{\text{GR front}} = \tan^{-1} \left( \frac{\text{mean mediolateral GRF}}{\text{mean vertical GRF}} \right) \cdot \frac{180^\circ}{\pi}
\]

\[
F_{\text{GR trans}} = \tan^{-1} \left( \frac{\text{mean anteroposterior GRF}}{\text{mean mediolateral GRF}} \right) \cdot \frac{180^\circ}{\pi}
\]

These represent modifications of the equations used by Otsuka, et al. (2014). Each athlete’s mean GRF was normalised by dividing by body weight.

4.2.8 Segment angles, joint angles and range of motion (Paper III)
The local coordinate systems (LCS) of the pelvis and thigh segments are shown in Figure 8. The pelvis segment angles were calculated with respect to the laboratory coordinate system using the ZXY Cardan rotation sequence. This corresponds to a set of rotations about: 1) the Z (mediolateral axis) of the pelvis (i.e. flexion/extension) 2) the floating axis formed from the cross product of the y axis of the thigh and the z axis of the pelvis (i.e. abduction/adduction) and 3) the y (vertical) axis of the thigh (i.e. internal/external rotation). This is identical to the joint coordinate system (JCS) proposed by Grood and Suntay (1983) (Visual3D).

The range of motion (RoM) of the pelvis was defined as the maximum pelvic angle before the end of the flight phase minus the corresponding minimum pelvic angle after the start event, for all three planes.

4.2.9 Angular momentum and external torque (Paper IV)
Whole-body angular momentum (\( \vec{H} \)) was calculated with respect to the CoM of the 15 segment wholebody model using the equation.

\[
\vec{H} = \sum_{i=1}^{15} \left[ I_i \vec{\omega}_i + (\vec{r}_i^{\text{CoM}} - \vec{r}_i^{\text{body}}) \times m_i (\vec{v}_i^{\text{CoM}} - \vec{v}_i^{\text{body}}) \right]
\]
where $\vec{r}_{CoM}^i$ and $\vec{q}_{CoM}^i$ are the position, and velocity vectors of the $i^{th}$ segment CoM for $i = 1$ to 15 segments, $\vec{w}_i$ is the $i^{th}$ segment angular velocity vector, $I$ and $m_i$ are the $i^{th}$ segment inertia matrix and mass respectively, and $\vec{p}_{body}$ and $\vec{q}_{CoM}^body$ are the position and velocity vectors of the whole-body CoM.

The angular momenta of various segments were summed into groups, for example, the angular momentum of the lower body consisted of the sum of the angular momenta of the feet, shanks, thighs and pelvis, and the angular momentum of the upper body was the sum of the angular momenta of the head and trunk, hands, forearms, and upper arms.

Angular momentum and external torque are related by the following equation (Young & Freedman, 2014):

$$\sum_{i=1}^{n} \tau_i = \vec{H}$$

where $\sum_{i=1}^{n} \tau_i$ is the vector sum of the external torques (i.e. the net torque) and $\vec{H}$ is the first derivative of angular momentum with respect to time.

External torque was normalised and made dimensionless by dividing by weight*leg length (Hof, 1996) and $\vec{H}$ was normalised by dividing by mass*height$^2$ (Hinrichs, 1987). As the resulting values for $\vec{H}$ were small they were multiplied by 1000 to give units of 0.001/s.

4.2.10 Induced acceleration analysis (Paper II)

Induced acceleration analysis (IAA) is a method for calculating how individual forces and moments contribute to the instantaneous acceleration of a system (Selbie, Hamill & Kepple, 2014). In Paper II, IAA was used to quantify the contributions of specific lower body muscles to the acceleration of the whole-body CoM.

The equations of motion for a multibody system are (Pandy, 2001; OpenSim):

$$[M] \ddot{\vec{q}} = \vec{g}(\vec{q}) + \vec{V} (\dot{\vec{q}}, \ddot{\vec{q}}) + \vec{E} (\dot{\vec{q}}, \ddot{\vec{q}}) + [R] \vec{F}_m$$

where $M$ is the matrix of segment masses and moments of inertia; $\vec{q}, \dot{\vec{q}}$ and $\ddot{\vec{q}}$, are the vectors of generalised position, velocity and acceleration, respectively; $\vec{g}$ is the generalised force vector due to gravity, $\vec{V}$ is the vector of velocity related forces (i.e. Coriolis and centripetal); $\vec{E}$ is a vector that contains the interactions with the external environment (i.e. the GRF), $R$ is the matrix of muscle moment arms and $\vec{F}_m$ is the vector of muscle forces.

The vector of induced accelerations caused by the forces is obtained by multiplying the terms on the right hand side of (11) by the inverse of the mass matrix $M$ to give:

$$\ddot{\vec{q}} = [M]^{-1} (\vec{g}(\vec{q}) + \vec{V} (\dot{\vec{q}}, \ddot{\vec{q}}) + \vec{E} (\dot{\vec{q}}, \ddot{\vec{q}}) + [R] \vec{F}_m)$$

(12)

Since the inverse mass matrix $[M]^{-1}$ will always be fully populated, a single muscle can contribute to the linear and angular acceleration of all the model segments (Zajac Neptune & Kautz, 2002). This is an example of dynamic coupling (Zajac & Gordon, 1989).

The contribution of an individual muscle can subsequently be determined by setting all terms on the right hand side of equation (12) to zero except: that muscle’s force (in $\vec{F}_m$) and its corresponding moment arm (in $[R]$) as well as that muscle’s contribution to $\vec{E}(\dot{\vec{q}}, \ddot{\vec{q}})$. This gives:

$$\ddot{\vec{q}} = [M]^{-1} (\vec{E} (\dot{\vec{q}}, \ddot{\vec{q}}) + [R] \vec{F}_m)$$

(13)

Equation (13) can then be solved to give the instantaneous acceleration caused by that muscle. In this thesis, IAA was performed using a generic whole-body musculoskeletal model with 22 segments and 37 degrees of freedom in OpenSim v3.3 (Delp et al., 2007).

4.3 Statistical methods (Papers I - IV)

Statistical analysis was performed using SPSS (IBM SPSS 24, IBM Corp., NY, USA) and Excel 2016 (Microsoft Corporation, Redmond, Washington, USA). Data were first checked for outliers using box and whisker plots and then tested for normality using the Shapiro-Wilk test. Statistical significance was considered at $p < 0.05$. 
4.3.1 Relationships between variables (Papers I and III)
The relationship between two variables was assessed using scatter plots. The plots were first examined visually to assess what function could best describe the data. Correlations between variables were tested with either Pearson’s r (for normally-distributed data) or Spearman rho (for non-normally distributed data). Correlations were considered very high for coefficients $r > 0.90$, high for $0.70 < r \leq 0.89$, moderate for $0.50 < r \leq 0.69$, and low for $r \leq 0.50$ (Hinkle et al., 2009).

4.3.2 Differences between the skating and narrow trials (Paper I)
Dependent t-tests were used for determining differences between the skating and narrow trials for; step width, step length, block time, contact time, anterior velocity, impulses, GRF vectors and external power.

4.3.3 Effect size (Paper I)
Effect size (Cohen’s d) was calculated to gain further insight regarding the practical significance of the results. Effect size was computed for each variable using:

$$\frac{\mu_{\text{Skating}} - \mu_{\text{Narrow}}}{\sigma_{\text{Skating}}}$$

where $\mu$ is the respective group mean and $\sigma_{\text{Skating}}$ is the standard deviation of the Skating group.

The effect size was defined as trivial (<0.20), small (0.20–0.49), medium (0.50–0.79) or large (>0.80) according to Cohen (1992).

5 Results and Discussion

5.1 Internal and ecological validity

5.1.1 Internal validity
In order to study if fatigue or learning effects could have influenced the results of the data collection, $P_{\text{NAH}}$ was plotted as a function of trial number for each athlete. The linear trendlines for $P_{\text{NAH}}$ revealed that these generally had a low gradient for all athletes with no consistent pattern for the direction of the slope between athletes or between skating and narrow trials. No athlete showed more than three consecutive trials of increasing or decreasing values. These results suggest that no significant learning or fatigue effect was present.

5.1.2 Ecological validity
To ensure the participants were not adversely influenced by performing in a laboratory setting, a pilot study was performed on a full size indoor running track. The vertical position of a marker placed on the processus spinosus of the C7 of the athletes at 2nd stance touchdown was compared for track and laboratory running. No significant differences were observed when the marker position was analysed with the Wilcoxon Signed Rank test. We thus assumed the laboratory setting was adequate for testing the athletes.

5.2 Effect on external forces when step width is restricted (Paper I)

5.2.1 Kinematic comparison of natural (Skating) step width to running inside a 0.30 m wide lane (Narrow)
Narrowing the running track reduced the group average step width (Narrow trials) by almost 40% compared to the skating trials (Table 4). No statistical differences were found for; block time, step length nor 1st stance contact time.
Table 4. Comparison of kinematic data for both skating and narrow trials.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Variable</th>
<th>Skating mean SD</th>
<th>Narrow mean SD</th>
<th>p value</th>
<th>Effect Size (Cohen's d)</th>
<th>Effect Size Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step width (mean foot to 1st step)*</td>
<td>0.31 0.08</td>
<td>0.19 0.03</td>
<td>&lt;0.01</td>
<td>1.38</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>Step length (mean foot to 1st step)</td>
<td>1.13 0.10</td>
<td>1.12 0.12</td>
<td>0.36</td>
<td>0.12</td>
<td>trivial</td>
</tr>
<tr>
<td></td>
<td>1st Stance Contact time (s)</td>
<td>0.21 0.01</td>
<td>0.20 0.01</td>
<td>0.59</td>
<td>0.15</td>
<td>trivial</td>
</tr>
<tr>
<td></td>
<td>Block time (s)</td>
<td>0.37 0.03</td>
<td>0.38 0.03</td>
<td>0.62</td>
<td>0.13</td>
<td>trivial</td>
</tr>
</tbody>
</table>

The presented values are the group average values for all athletes and all trials (i.e. the mean of the mean). *Significant difference between skating and narrow trials (p < 0.05). Adapted from Sandamas et al. (2019).

5.2.2 Impulses and GRF vector magnitudes

Relative medial and vertical block impulses were higher in the skating trials, and during the 1st stance phase the medial and propulsive components were higher for the skating trials (Table 5). The block phase average GRF vector magnitudes were higher in mediolateral and vertical directions for the skating trials, while during the 1st stance phase the average mediolateral GRF magnitude was higher for the skating trials.

Table 5. Starting block and 1st step: relative impulses and average ground reaction force vector magnitudes.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Variable</th>
<th>Skating mean SD</th>
<th>Narrow mean SD</th>
<th>p value</th>
<th>Effect Size (Cohen's d)</th>
<th>Effect Size Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting</td>
<td>Block</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anteroposterior GRF (BW)</td>
<td>0.87 0.1</td>
<td>0.86 0.1</td>
<td>0.38</td>
<td>0.13</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Mediolateral GRF (BW)*</td>
<td>0.06 0.02</td>
<td>0.02 0.01</td>
<td>&lt;0.01</td>
<td>1.83</td>
<td>large</td>
<td></td>
</tr>
<tr>
<td>Vertical GRF (BW)*</td>
<td>1.15 0.02</td>
<td>1.16 0.02</td>
<td>0.03</td>
<td>0.59</td>
<td>medium</td>
<td></td>
</tr>
<tr>
<td>Resultant GRF (BW)</td>
<td>1.44 0.07</td>
<td>1.44 0.07</td>
<td>0.93</td>
<td>0.01</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Anteroposterior impulse (m/s)</td>
<td>3.21 0.16</td>
<td>3.19 0.16</td>
<td>0.37</td>
<td>0.12</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Mediolateral impulse (m/s)*</td>
<td>0.54 0.07</td>
<td>0.59 0.08</td>
<td>0.01</td>
<td>-0.6</td>
<td>medium</td>
<td></td>
</tr>
<tr>
<td>Vertical impulse (m/s)</td>
<td>0.23 0.1</td>
<td>0.08 0.05</td>
<td>&lt;0.01</td>
<td>1.48</td>
<td>large</td>
<td></td>
</tr>
<tr>
<td>Resultant impulse (m/s)</td>
<td>3.27 0.15</td>
<td>3.25 0.16</td>
<td>0.32</td>
<td>0.12</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>1st Step</td>
<td>Anteroposterior GRF (BW)</td>
<td>0.64 0.06</td>
<td>0.63 0.04</td>
<td>0.32</td>
<td>0.28</td>
<td>small</td>
</tr>
<tr>
<td>Mediolateral GRF (BW)*</td>
<td>-0.16 0.05</td>
<td>-0.08 0.04</td>
<td>&lt;0.01</td>
<td>1.49</td>
<td>large</td>
<td></td>
</tr>
<tr>
<td>Vertical GRF (BW)</td>
<td>1.36 0.09</td>
<td>1.35 0.13</td>
<td>0.84</td>
<td>0.05</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Resultant GRF (BW)</td>
<td>1.51 0.1</td>
<td>1.49 0.12</td>
<td>0.54</td>
<td>0.18</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Net Anteroposterior impulse (m/s)</td>
<td>1.29 0.06</td>
<td>1.26 0.04</td>
<td>0.07</td>
<td>0.54</td>
<td>medium</td>
<td></td>
</tr>
<tr>
<td>Braking impulse (m/s)</td>
<td>0.04 0.04</td>
<td>0.03 0.02</td>
<td>0.34</td>
<td>0.13</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Propulsive impulse (m/s)*</td>
<td>1.33 0.06</td>
<td>1.29 0.05</td>
<td>0.04</td>
<td>0.59</td>
<td>medium</td>
<td></td>
</tr>
<tr>
<td>Vertical impulse (m/s)</td>
<td>0.71 0.18</td>
<td>0.71 0.28</td>
<td>0.94</td>
<td>0.02</td>
<td>trivial</td>
<td></td>
</tr>
<tr>
<td>Net Mediolateral impulse (m/s)*</td>
<td>-0.33 0.1</td>
<td>-0.17 0.1</td>
<td>&lt;0.01</td>
<td>1.48</td>
<td>large</td>
<td></td>
</tr>
</tbody>
</table>

The presented values are the group average values for all athletes and all trials (i.e. the mean of the mean). *Significant difference between skating and narrow trials (p < 0.05). Adapted from Sandamas et al. (2019).

5.2.3 Relationships between impulses and 1st step width

A high positive correlation was found between relative medial block impulses and normalised step width (Figure 9a) for the skating and narrow trials, respectively. Low correlations were found between relative anterior block impulses and step width (r = -0.274, p = 0.091 skating and r = 0.039, p = 0.812 narrow) or between vertical block impulses and step width (r = -0.061, p = 0.713 skating and r = -0.066, p = 0.691 narrow). A moderate positive correlation was found between normalised step width and 1st stance mediolateral impulses (Figure 9b). No correlations were found between normalised step width and; braking (r = -0.240, p = 0.116 skating and r = -0.062, p = 0.702 narrow), propulsive (r = -0.143, p = 0.356 skating and r = 0.083, p = 0.606 narrow) vertical (r = -0.220, p = 0.151 skating, r = 0.305, p = 0.053 narrow) or the net anteroposterior impulses (r = 0.027, p = 0.864 skating), r = 0.161, p = 0.316 narrow).

Figure 9. Relationships between (a) starting block net relative medial impulse and normalised 1st step width and (b) normalised step width and 1st stance net relative medial impulse. A high (Figure 9a) and moderate (Figure 9b) correlation was found between these variables. Note as opposed to Figure 9a, Figure 9b shows medial impulse on the y-axis because during the 1st stance, step width was defined as the independent variable.

5.2.4 Orientation of the average external force vector

During the skating trials the average GRF vector was directed more medially towards the side of the rear (swing) leg during the block phase and more medially during the 1st stance phase than in the narrow trials (Figure 10 and Table 6).
Figure 10. Visual representation of the ensemble average normalised GRF in the three orthogonal planes for the block phase (top row) and 1st stance phase (bottom row). From Sandamas et al. (2019).

Table 6. Mean ground reaction force angles during the block and 1st stance phases.

<table>
<thead>
<tr>
<th>Phase</th>
<th>GRF Angle</th>
<th>Skating mean (⁰)</th>
<th>SD</th>
<th>Narrow mean (⁰)</th>
<th>SD</th>
<th>p value</th>
<th>Effect Size</th>
<th>Effect Size (Cohen's d)</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Block</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,sag}$</td>
<td>52.8</td>
<td>2.9</td>
<td>53.7</td>
<td>2.9</td>
<td>0.07</td>
<td>0.31</td>
<td>small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,front}$*</td>
<td>3.1</td>
<td>1.2</td>
<td>1.1</td>
<td>0.6</td>
<td>&lt;0.01</td>
<td>1.59</td>
<td>large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,trans}$*</td>
<td>4.8</td>
<td>3.2</td>
<td>1.9</td>
<td>1.9</td>
<td>&lt;0.01</td>
<td>0.88</td>
<td>large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Step</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,sag}$</td>
<td>64</td>
<td>1.7</td>
<td>64.8</td>
<td>1.1</td>
<td>0.13</td>
<td>0.49</td>
<td>small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,front}$*</td>
<td>-6.8</td>
<td>2.2</td>
<td>-3.5</td>
<td>1.8</td>
<td>&lt;0.01</td>
<td>1.55</td>
<td>large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{GR,trans}$*</td>
<td>-9.6</td>
<td>4.6</td>
<td>-4</td>
<td>3.9</td>
<td>0.01</td>
<td>1.22</td>
<td>large</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Significant difference between skating and narrow trials (p < 0.05). Adapted from Sandamas et al. (2019).

Alternatively, ratio of forces can be used for analysing the average force vector. Ratio of forces results are presented in Appendix A2.

5.2.5 Transverse plane CoM motion

In the transverse plane, in addition to forward motion, the motion of the athletes’ CoM was first lateral towards the rear leg during the block phase and then lateral towards the swing leg during the stance phase (Figure 11). More pronounced mediolateral motion was seen in the skating trials.

Figure 11. Example of the mean transverse plane motion of the CoM from Start to 1st step toe-off for a typical participant. Skating trials are depicted with the solid line and the narrow trials with the dashed line. From Sandamas et al. (2019).

5.2.6 Summary of the effect on external forces when step width is restricted

Reducing step width caused a reduction in medial block impulses and an increase in vertical block impulses. These differences can also be seen in the average 3D GRF vectors (Figure 10). Reducing step width caused a reduction in $F_{GR,trans}$ angle and average mediolateral block vectors and an increase in the average vertical block GRF vector. The greatest differences between the skating and narrow styles during the block phase were seen in the mediolateral direction. Although the mediolateral impulses are the smallest of the three, they are not negligible. An increase in the vertical impulse could cause a greater block exit angle, and since a high block exit angle is detrimental to performance (Harland & Steele, 1997) it is possible that there exists a small trade-off in terms of pushing direction.

The mean relative anteroposterior block impulse found in this study (3.2 m/s) was similar to that reported by Coh et al. (1998) for sprinters of similar ability. The average normalised step length was similar to that reported in the studies of Bezodis et al (Bezodis, et al., 2014; Bezodis, Salo, & Trewartha, 2015). Although the mean skating step widths (0.31 m) found in this study were similar to the 1st stance step width of 0.31 m
reported by Otsuka, et al. (2014), the mean relative mediolateral block impulse of 0.23 m/s found in this study was nearly double that of 0.14 m/s reported by Otsuka, et al. (2014) for sprinters of similar ability, height and weight. The reason for this difference in reported mediolateral impulses is unclear.

The relationship between mediolateral block forces, mediolateral impulses and step width is consistent with findings of McClay and Cavanagh (1994) for running. In accordance with the laws of motion the greater mediolateral motion of the CoM seen during the skating trials (Figure 11) reflects the greater external mediolateral forces during the block and first stance phases. Therefore, the athletes push more in the mediolateral direction when performing a skating style start.

In conclusion, considerable mediolateral impulses and mediolateral deviation of the CoM were found to be a natural part of sprint acceleration when utilising a skating style sprint start technique using starting blocks. By reducing step width, a reduction in mediolateral impulses and mediolateral deviation of the CoM was seen.

5.3 Effect on lower body muscle forces when step width is restricted (Paper II)

As Paper I compared the difference in external forces between the skating and narrow trails, the focus of Paper II was to compare the difference in internal forces between the skating and narrow trials. More specifically: does a narrow 1st step offer a muscular advantage to anterior CoM propulsion compared to a natural wide step?

Due to the time required to perform a 3D whole-body musculoskeletal forward simulation, four athletes (two male and two female) were analysed. The two male athletes with the widest normalised 1st step width and both female athletes were chosen for this study.

5.3.1 Kinematics, PNAH and external forces

The mean normalised step width was 0.37 ± 0.04 in the skating and 0.15 ± 0.04 in the narrow trials, for the four athletes. The contact phase was an average of 0.02 s longer in the narrow trials than in the natural trials. The mean PNAH was 0.80 ± 0.05 in the skating trials and 0.73 ± 0.08 in the narrow trials. Peak anterior and vertical GRF were lower in the narrow trials than in the skating trials, by approximately 0.20 times body weight (BW). Peak medial GRF was lower in the narrow trials by approximately 66 %.

5.3.2 Muscle-induced CoM acceleration

The soleus muscle contributed the most to both propulsion and support in the skating trials (Figure 12). When step width was restricted, the contributions from most muscles to propulsion and support were reduced. The reductions were most noticeable in the contributions from the soleus and gastrocnemius. The soleus contribution was lower from about 25 % of the stance phase and thereafter decreased throughout the rest of the stance phase. The gastrocnemius contribution to propulsion and support was distinctly less during the final 40% of stance in the narrow trials.

Figure 12. Muscle contributions to body CoM acceleration over the stance phase, averaged over the four participants, shown as rays at every 2% of the stance phase between 14 and 82% of the stance phase. Each ray is the resultant vector of the vertical and anteroposterior accelerations. Note that the scale of the y-axis is different for the biceps femoris and adductors. Total (i.e. resultant) CoM accelerations (top row) are the average of each participant’s measured GRF divided by his/her mass (red). The sum of all the muscle contributions represents the sum of the contributions from all muscle actuators in the model for the skating (blue) and the narrow (green) trials. Also note that in this Figure, the title Natural refers to the skating style.
The vasti muscle group (vastus intermedius, lateralis and medialis) was a major contributor to support as well as contributing the most to medial CoM acceleration in both the skating and narrow trials (Figure 13). The soleus made a distinctly lower contribution to medial acceleration in the narrow trials. The remaining muscles were also affected by a reduced step width but to a lesser amount.

In conclusion, when step width was restricted practically all muscles contributed less to propulsion and support, particularly the muscle spanning the ankle and knee joints. Therefore, based on our simulation, a narrower step width appears to offer no muscular advantage to enhancing performance.

5.4 Assessment of 3D lower body kinematics (Paper III)

The 3D description of joint angles provided by Debaere et al. (2013) suggests that pelvic motion (rather than simply hip adduction and/or internal rotation) could be the primary kinematic cause of the swing leg moving medially in front of the body. Therefore, one aim of Paper III was to ascertain if the medial thigh motion during the SP phase is primarily coupled to a combination of 3D pelvis rotations as opposed to simply hip internal rotation and/or adduction of the swing leg. Another aim was to determine the relationships between block phase kinematics, 1st step width and performance.

5.4.1 Three dimensional pelvis motion

Although the majority of pelvic motion was found in the sagittal plane (pelvis tilt), a considerable amount of pelvic list and rotation from the Start to the mid-flight phase were observed (Figure 14, and Table 7).
Figure 14. Pelvic segment angles from start to 1st stance toe-off (normalised to 100 points) in the sagittal (a), frontal (b) and transverse (c) planes for all participants. The black line represents the group mean. The vertical lines represent (from left to right) the key events of rear block exit, block exit and toe-off. The position of the vertical lines are approximately drawn for the group of athletes. 1st, 2nd, 3rd, 4th and 5th refers to the top five athletes ranked according to their $P_{NAHB}$ (Table 7). From Sandamas et al. (2020).

The plots of the group mean pelvis segment angles as a function of time were similar to the graphs of the group mean pelvis segment angles illustrated by Debaere et al. (2013). In contrast to Debaere et al. (2013), the mean curves from each athlete’s individual trials are also displayed and so the variation between athletes can be observed. The greatest deviation from the group mean can be seen in the single push phase for pelvic rotation (Figure 14c).

The relationships between pelvis RoM and step width is discussed in 5.4.3 and performance in 5.5.2.

Table 7. Each participant’s Pelvic RoM, normalised block power ($P_{NAHB}$), normalised 1st step width and normalised 1st stance power ($P_{NAH}$). Their respective group ranking for $P_{NAHB}$ is also given. From Sandamas et al. (2020).

<table>
<thead>
<tr>
<th>Sprites</th>
<th>Block Phase</th>
<th>$P_{NAHB}$</th>
<th>RoM (°) Block and Flight Plane</th>
<th>Corresponding 1st Stance Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.62</td>
<td>1</td>
<td>41 15 19</td>
<td>0.31 0.94</td>
</tr>
<tr>
<td>b</td>
<td>0.54</td>
<td>2</td>
<td>46 9 8</td>
<td>0.28 0.76</td>
</tr>
<tr>
<td>c</td>
<td>0.51</td>
<td>3</td>
<td>41 15 22</td>
<td>0.35 0.85</td>
</tr>
<tr>
<td>d</td>
<td>0.50</td>
<td>4</td>
<td>29 13</td>
<td>0.38 0.78</td>
</tr>
<tr>
<td>e</td>
<td>0.48</td>
<td>5</td>
<td>42 15 26</td>
<td>0.26 0.65</td>
</tr>
<tr>
<td>f</td>
<td>0.46</td>
<td>6</td>
<td>30 17 17</td>
<td>0.19 0.83</td>
</tr>
<tr>
<td>g</td>
<td>0.45</td>
<td>7</td>
<td>23 14</td>
<td>0.37 0.79</td>
</tr>
<tr>
<td>h</td>
<td>0.43</td>
<td>8</td>
<td>23 18 14</td>
<td>0.37 0.91</td>
</tr>
<tr>
<td>i</td>
<td>0.42</td>
<td>9</td>
<td>41 15 15</td>
<td>0.37 0.87</td>
</tr>
<tr>
<td>j</td>
<td>0.42</td>
<td>10</td>
<td>21 15 15</td>
<td>0.35 0.87</td>
</tr>
<tr>
<td>k</td>
<td>0.41</td>
<td>11</td>
<td>45 13 8</td>
<td>0.21 0.57</td>
</tr>
<tr>
<td>Mean</td>
<td>0.48</td>
<td></td>
<td>35 15 15</td>
<td>0.31 0.78</td>
</tr>
<tr>
<td>SD</td>
<td>0.06</td>
<td></td>
<td>10 5</td>
<td>0.07 0.12</td>
</tr>
</tbody>
</table>

* denotes the female athletes.

5.4.2 Kinematic reason for medial thigh motion of the swing leg

The largest changes in the rear leg hip joint angles were seen in the sagittal plane (Figure 15). The group mean (SD) rear hip RoM from rear block exit to the instant of peak pelvis list during the flight phase was: 43 (7)° flexion, 2 (7)° abduction and 7 (3)° internal rotation. The group mean (SD) hip joint angles at the instant of peak pelvis list were: 82 (8.6)° flexion, 1.5 (4.4)° adduction and 5.2 (8.4)° internal rotation.

The largest changes in the rear leg hip joint angles were seen in the sagittal plane (Figure 15). The group mean (SD) rear hip RoM from rear block exit to the instant of peak pelvis list during the flight phase was: 43 (7)° flexion, 2 (7)° abduction and 7 (3)° internal rotation. The group mean (SD) hip joint angles at the instant of peak pelvis list were: 82 (8.6)° flexion, 1.5 (4.4)° adduction and 5.2 (8.4)° internal rotation.

Figure 15. Ensemble group average rear leg hip angles with respect to the pelvis segment from start to 1st stance toe-off (normalised to 100 points). Positive hip angles represent hip flexion, abduction and internal rotation. The vertical lines represent (from
left to right) the key events of rear block exit, block exit and touchdown. From Sandamas et al. (2020).

During the block and 1st flight phases both hip abduction/adduction and hip internal/external rotation were very small compared to hip flexion/extension (Figure 15) for the swing leg. Combining this result with the description of pelvic segment angles shown in Figure 14, indicates that it is pelvis motion, and not simply hip adduction and/or hip internal rotation that is the primary kinematic reason that the swing leg moves medially in front of the athlete during the SP phase.

5.4.3 The relationship between pelvis RoM and 1st step width
A very high positive correlation was found for the relationship between pelvic list RoM and 1st step width ($r = 0.799$, $p = 0.003$) (Figure 16a). No correlations were found for the relationships between pelvic rotation RoM and 1st step width nor pelvic tilt RoM and 1st step width (Figure 16b & 16c).

5.5 Performance (Papers I and III)
The kinematic origin of the medial movement of the swing leg during the skating style start was shown to be a combination of pelvic rotation and pelvic list plus hip flexion of the swing leg (section 5.4.2). However, of particular interest to coaches and athletes is how these lower body movement patterns relate to performance. More specifically, how is performance ($P_{NAHB}$ and $P_{NAH}$) affected when 1st step width is restricted and is performance related to block phase Pelvic RoM?

5.5.1 Relationships between performance and 1st step width (Papers I and III)
No statistical difference was found between the skating and narrow trials for $P_{NAHB}$ (Table 8). Although a small effect size was found during stance between the skating and narrow trials for $P_{NAH}$, it was not statistically significant ($p = 0.18$).

Table 8 Starting block and 1st stance external power.

<table>
<thead>
<tr>
<th>Stance Phase</th>
<th>$P_{NAHB}$</th>
<th>$P_{NAH}$</th>
<th>p value</th>
<th>Effect Size (Cohen’s d)</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Block</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>p value</td>
</tr>
<tr>
<td>$P_{NAHB}$</td>
<td>0.46</td>
<td>0.07</td>
<td>0.43</td>
<td>0.07</td>
<td>0.33</td>
</tr>
<tr>
<td>1st Step Phase</td>
<td>$P_{NAH}$</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>$P_{NAH}$</td>
<td>0.78</td>
<td>0.09</td>
<td>0.73</td>
<td>0.08</td>
<td>0.18</td>
</tr>
</tbody>
</table>

The presented values are the group average values for all athletes and all trials (i.e. the mean of the mean). Dependent t-tests were used to determine statistical difference between the skating and narrow trials.
A comparison of each athletes’ unrestricted step width and performance was performed. No significant correlations were found for the relationships between $P_{\text{NAHB}}$ and step width ($r = 0.096$, $p = 0.780$) nor between step width and $P_{\text{NAH}}$ ($r = 0.378$, $p = 0.251$) (Figure 17).

Figure 17. Relationships between normalised 1st step width and: block performance (a), and 1st stance performance (b). No linear correlations were found between these variables. 1st, 2nd, 3rd, 4th and 5th refers to the top five athletes ranked according to their $P_{\text{NAHB}}$. Note as opposed to Figure 17a, Figure 17b shows external power on the y-axis because during the 1st stance, step width was defined as the independent variable. From Sandamas et al. (2020).

5.5.2 Relationships between block phase pelvis RoM and performance (Paper III)

No significant correlations were found for the relationships between pelvic RoM and $P_{\text{NAHB}}$ (Figure 18).

Figure 18. Relationships between pelvic list (a), rotation (b) and tilt (c) RoM and block phase performance. 1st, 2nd, 3rd, 4th and 5th refers to the top five athletes ranked according to their $P_{\text{NAHB}}$. From Sandamas et al. (2020).

To summarise performance; no statistical difference was found for block phase nor 1st stance phase performance when step width was restricted. However, a small effect size for 1st stance performance in favour of the skating trials highlights a possible decrease in performance when step width was restricted. Furthermore, block power ($P_{\text{NAHB}}$) did not correlate with normalised 1st step width and 1st step width did not correlate with 1st stance power ($P_{\text{NAH}}$). In addition pelvic list, tilt or rotation RoM did not correlate with block power ($P_{\text{NAHB}}$). This suggests that neither step width nor the amount of pelvic RoM is the discriminator of superior performance levels.

In conclusion, reducing 1st step width caused; a reduction in medial impulses, a less medially pointing GRFv and a reduction in mediolateral deviation of the CoM. However, there was not a sufficient increase in the anteriorly directed GRFv in the narrow...
trials to register a benefit to performance. From a coaching point of view, the idea that if the athlete adopts this awkward looking technique during the block phase with the swing leg passing medially in front of the body or uses a wide initial step is detrimental to performance, was not supported by these studies. Therefore, trying to reduce pelvic RoM or changing frontal and transverse plane hip joint angles to minimise the flailing leg motion is unlikely to lead to an improvement in performance.

5.6 Angular momentum during the block and 1st stance phase of the sprint start (Paper IV)

Although the sprint start involves 3D motion of all body segments, the studies so far have not considered the influence of the upper-body segments. Investigating the sprint start using the basic principles governing whole-body rotation is a basis for understanding why segment motions take place outside the sagittal plane. Therefore, the aim of the final study was to analyse whole-body angular momentum and the contributions of segments and segment groups to whole-body angular momentum.

5.6.1 Whole-body and segment angular momentum

Considering that the athletes must raise their upper body out of the crouched initial position it was not surprising to see that the largest peak magnitudes and range of the orthogonal components of whole-body $H$ were found in the mediolateral ($z$) direction (Figure 19 and Table 9). The upper body contributed more to $H_z$ than the lower body in the mediolateral direction (Figure 20a). During the DP phase the combined head-and-trunk contributed most to positive $H_z$ (Figure 20b), i.e. the angular momentum corresponding to the sprinter rotating upwards in the sagittal plane. After the DP phase, the largest segment contributions were seen in the legs. The contributions from the left and right legs were similar in magnitude but opposite in sign and so tended to cancel each other out.

The larger contribution of the upper body to $H_z$ can mainly be explained by the fact that the angular momentum due to the alternating motion of the legs largely cancelled each other (Figure 20b). The arms, likewise, rotated in opposite directions and so their components also cancelled each other. However, not only was the rear arm contribution small, the front arm rotated in the same direction as the head and trunk and therefore contributed to the net upper body $H_z$ during the block phase. The inverse result was seen during stance for the arms’ contribution, as the rear arm rotated in the same direction as the head and trunk its contribution was higher than the front arm. A similar sinusoidal graph pattern for the legs’ contribution to mediolateral angular momentum was also found in running (Hinrichs, 1987).
The corresponding external torque and the net external force vectors with respect to the CoM are illustrated in Appendix B.

Table 9. Mean values of the peak–to-peak ranges of angular momentum (\(\vec{H}\)) during the block and 1st stance phases.

<table>
<thead>
<tr>
<th>Angular Momentum Ranges (*0.001/s)</th>
<th>Block Phase</th>
<th>1st Stance Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean  SD</td>
<td>Mean  SD</td>
</tr>
<tr>
<td>Mediolateral ((H_z))</td>
<td>58.60 (9.47)</td>
<td>43.20 (13.9)</td>
</tr>
<tr>
<td>Anteroposterior ((H_x))</td>
<td>33.13 (6.40)</td>
<td>16.50 (8.26)</td>
</tr>
<tr>
<td>Vertical ((H_y))</td>
<td>22.06 (6.01)</td>
<td>18.75 (4.13)</td>
</tr>
</tbody>
</table>

In the anteroposterior (x) direction nearly all the \(H_x\) was found in the upper body (Figure 21a) of which the major contributors were the rear arm during the block phase and the front arm during stance (Figure 21b). The rear arm’s large contribution seen during the block phase is likely related to asymmetrical arm motion and joint angular velocities. During the block phase the peak rear shoulder angular velocity has been reported to be more than twice that of the front shoulder (Slawinski et al., 2010). During the block phase the rear shoulder extends rapidly, whereas the front shoulder first extends during the DP phase and then flexes during the SP phase and is kept close to the midline of the body (Slawinski et al., 2010). Thus it is possible that a combination of the rear arm’s higher angular velocity and its CoM moving away from the anteroposterior axis could cause the major contribution to be found in the rear arm during the block phase. In contrast during stance, the rear arm approaches the midline of the body while the front arm moves laterally away from it which could explain the greater contribution from the front arm.

In the vertical (y) direction, the net upper body and net lower body contributions were approximately equal in magnitude, equal in phase but opposite in sign (Figure 22a). The exception to this was during the DP phase when the contribution from the upper body was small and in the same direction as the contribution from the lower body.

The general pattern of the net upper- and lower body contributions to \(H_y\) during the SP and 1st stance phases was similar to those reported for running by Hinrichs (1987). That is, the graphs of the net upper- and lower body contributions were similar in magnitude, similar in phase but opposite in sign. The effect of these cancellations was that the \(H_y\) remained relatively close to zero throughout the start phase (Figures 19 and 22a). Hinrichs, (1987) described how the vertical component of upper- and lower body angular impulses in running, function like an action-reaction pair in accordance with Newton’s 3rd law. The results of this study suggest a similar concept occurs about the vertical axis during the sprint start.

It is also interesting to note how the arm and leg segment groups’ coordinated motion contribute to the whole-body angular momentum. During the SP phase the front arm and rear (swing) leg approximately balance each other, whereas during stance, the rear arm and front (swing) leg approximately balance each other. Bhowmick & Bhattacharyya (1988) described the possible role of the arms to balance the sagittal plane lower body angular momentum during the sprint start, a notion supported by coaches (Jones et al., 2009). The results of Paper IV suggest that the arms are more effective in balancing the angular momentum of the legs in the transverse plane.
Figure 20. Ensemble average components of normalised angular momentum in the mediolateral ($H_z$) direction. The net wholebody angular momentum plus the lower and upper body components are shown in figure (a). Positive values indicate a counter-clockwise rotation when viewed from the right side. The angular momentum of the groups of segments are shown in figure (b). The vertical lines represent the key events of rear block exit, block exit, touchdown and toe-off, and were approximated for the group of athletes.

Figure 21. Ensemble average components of normalised angular momentum in the anteroposterior ($H_x$) direction. The net wholebody angular momentum plus the lower and upper body components are shown in figure (a). Positive values indicate a counter-clockwise rotation when viewed from the front. The angular momentum of the groups of segments are shown in figure (b). The vertical lines represent the key events of rear block exit, block exit, touchdown and toe-off, and were approximated for the group of athletes.
6 Conclusions

The primary kinematic reason behind the lower body posture that sprinters adopt during the block phase whereby the swing leg moves medially in front of the body, was shown to be a combination of 3D pelvis rotations as opposed to simply hip internal rotation or adduction of the swing leg.

Although medial impulses and block phase pelvic list RoM were shown to correlate positively to step width, neither step width nor pelvis RoM were found to be related to performance. Furthermore, when 1st step width was restricted no muscular advantage to anterior propulsion was found nor was performance improved.

The regulation of angular momentum in the frontal and transverse planes suggests a strategy to keep the net external moment in the frontal and transverse planes close to zero and thus prevent the high external (reaction) forces from causing excessive whole-body rotation. Therefore, lower limb motion outside the sagittal plane during the starting phase might be part of this strategy.

These results of this thesis suggest that reducing the amount of pelvic motion or reducing step width (i.e. trying to curtail a skating style technique) is unlikely to lead to an immediate improvement in performance.
7 Limitations and future perspectives

Practitioners should bear in mind that the conclusions of this thesis are based on a group study design so care must be taken when generalising the results. Although the statistical analysis of the pooled data showed no immediate benefit from narrowing the 1st step, it cannot be stated with complete confidence that all sprinters would not benefit from altering their initial step width. Furthermore, this was a cross sectional study and so a question that cannot be answered by this thesis is: what if the athletes were to train over a period of time with reduced step width? Which leads to a further question: is it ethical to try to change a sprinter’s technique without a clear reason when our results suggest no benefit?

In general, the greater the sample size the greater the statistical power. Eleven competitive sprinters were the maximum we could obtain within the inclusion criteria and the time and financial restrictions of this project. However, small sample sizes are common in biomechanics research, which is why multiple trials (for increasing statistical power) and reporting effect sizes are recommended (Bates, Dufek, & Davis, 1992; Mullineaux, Bartlett, & Bennett, 2001). Study II was restricted to the analysis of four sprinters due to the processing time required in complex musculoskeletal modelling. However, the key statistical results from the studies using 10 or more sprinters (Papers I and III), had high correlations or large effect size and therefore a larger sample size would not necessarily have changed the conclusions.

Although most sprint coaches agree that the role of the arms is important, there is no common agreement regarding which block phase arm technique to use (Jones et al., 2009). Due to the linked system of the body, upper body segment motion will influence the orientation of the GRFv (Zatsiorsky, 2002; Kugler & Janshen., 2010). Despite this clear mechanical concept, there is a paucity of information regarding the role of the arms in the sprint start. Paper IV showed how segment group angular momenta cancellations were seen in all planes and particularly how the upper- and lower body contributions cancelled each other in the transverse plane. Therefore, future studies could investigate the degree to which the non-sagittal plane motion of the lower body is related to different arm motion techniques.
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• And finally to my daughters, for reminding daddy there is a life outside PhD work ☺☺.

Det övergripande syftet med avhandlingen var att ur ett biomekaniskt perspektiv belysa a) grundläggande bakomliggande kinematiska och mekaniska orsaker för tekniken och b) hur både prestation och muskulära bidrag till prestation påverkas när stegbredden begränsades. Syftet med begränsad stegbredd var att minska sidledsrörelser.

Specifika kinematiska och kinetiska variabler registrerades från 11 tävlingssprinters (nio män, två kvinnor) som utförde 15 m sprintstarter. Tredimensionell kinematik, reaktionskraft och elektromyografiska data samlades från blockfasen till slutet av det första steget. Varje sprinter utförde fem försök med sin naturliga teknik och fem försök med stegbredden begränsad till en 0,3 m bred löpbana. En helkroppsmodell med 15 segment och en muskelmodell skapades och användes för att beräkna relevanta parametrar. Normaliserad genomsnittlig horisontell extern effekt användes som prestationsmått.

En kombination av upprätt lutning och bäckenrotation (men inte höftadduktion) var relaterad till en medial rörelse av svängbenets lår under "single push phase". När stegbredd inte var begränsad, korrelerade bäckens lutning och medialt riktade impulser med stegbredden, men stegbredd var inte relaterad till prestation. När stegbredden var begränsad var den normaliserade genomsnittliga reaktionskraftvektorn mer framåtriktad, men bidraget av nedre extremiteternas muskler till accelerationen reducerades och ingen omedelbar prestationsförbättring kunde påvisas.

Den primära kinematiska orsaken bakom kroppshållningen och rörelsemönstret som sprintarna antar under blockfasen, varigenom svängbenet rör sig medialt framför kroppen orsakas av en kombination av tredimensionella bäckenrotationer snarare än bara

9 Sammanfattning
höftens internrotation eller adduktion av svängbenet. Att försöka minska rörelseomfånget i bäckenet eller att minimera den svängande benrörelsen leder troligen inte till förbättrad prestation. Uppfattningen att denna teknik är ineffektiv stöddes därför inte av forskningen som presenterades i denna avhandling.

10 References


Williams, W. L. (1980). Sprinting, Nagahara, R., Mi

Appendix A. Some additional results for the skating and narrow trials

This section contains additional results for some commonly measured parameters. These were not included in the articles, but could be of value for an interested reader.

A1. First stance resultant joint moments, joint power and joint work

An example of 3D rear (stance) leg joint moments during 1st stance in the skating (grey) and narrow (green) trials for the top performing female athlete (100 m PB: 11.30 s) are shown in Figure 23. Joint moments were calculated in Visual3D using Newton-Euler inverse dynamic procedures (Selbie, Hamill, & Kepple, 2014). Force plate and kinematic data were filtered at the same frequency (12 Hz) to prevent artefacts during ground impacts (Bezodis et al., 2013; Bisseling & Hof, 2006). No statistically significant differences were found for the 1st stance peak (initial, mid-and late stance) 3D resultant joint moments between the skating and narrow trials.
Figure 23. An example of normalised hip, knee and ankle joint moments during 1st stance for one participant. Mean (solid line) and standard deviation (shaded), for the skating (grey) and narrow (green) trials. Positive values represent extension (plantar flexion), abduction (eversion) and internal rotation (adduction). Joint moments are expressed with respect to the JCS.

No statistically significant differences were found between the skating and narrow trials for peak joint power nor peak joint work.

A2. Ratio of forces

An alternative way of assessing the orientation of the GRF vector is ratio of forces (RoF). Ratio of forces is the mean ratio of the anteroposterior component of the GRF to the resultant GRF for the contact time (Morin et al., 2011). Although no statistically significant differences were found between the trials (dependent t-test), a small effect size was recorded (Table 10). This might suggest a slightly more vertically oriented GRF vector in the narrow trials as illustrated for the sagittal plane in Figure 10 and could also reflect the larger block phase vertical impulse recorded for the narrow trials (Table 5). Neither of which are likely to benefit performance.

Table 10. Block and 1st stance ratio of forces.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Skating RF (%)</th>
<th>SD</th>
<th>Narrow RF (%)</th>
<th>SD</th>
<th>p value</th>
<th>Effect Size (Cohen’s d)</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Block</td>
<td>60.35</td>
<td>3.93</td>
<td>59.14</td>
<td>4.07</td>
<td>0.089</td>
<td>0.31</td>
<td>small</td>
</tr>
<tr>
<td>1st Step</td>
<td>42.0</td>
<td>2.60</td>
<td>41.0</td>
<td>1.70</td>
<td>0.226</td>
<td>0.30</td>
<td>small</td>
</tr>
</tbody>
</table>

A3. Touchdown distance

The mean TD for the skating trials was -0.111 ± 0.034 m and the narrow trials -0.110 ± 0.046 m. No statistically significant difference were found between these trials (p = 0.883).
Appendix B. External torque and the GRF vector(s) during the start phase
Figure 24. Ensemble average normalised external torque in the vertical (a), anteroposterior (b), and mediolateral (c) directions for 9 athletes. External torque was calculated as the first derivative of $\vec{H}$ with respect to time. The skeleton images illustrate the direction of the net external force vector(s) with respect to the CoM (filled circle) of the sprinter in the three orthogonal directions for a typical participant. Positive values of $\tau_z$, $\tau_x$ & $\tau_y$ indicate a counter-clockwise rotation when viewed from the right side, the front and above, respectively.