# Principal component analysis identifies differences in ice hockey skating stride between high and low calibre players

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## Abstract

The objective was to compare lower extremity joint angles during full stride skating on ice between high and low calibre hockey players. High (n=8) and low (n=8) calibre male participants completed full stride skating on ice for two to five trials. A 10-camera motion capture system collected kinematic data. Ankle, knee, and hip angles were calculated about joint coordinate systems. Principal component analysis (PCA) identified important angle characteristics and each trial was scored against principal components (*PC-scores*). Hierarchical linear models examined the relationship between *PC-scores* and skill level with and without controlling for speed. High calibre participants were associated with greater ankle inversion during push-off and recovery ($p<0.001$), greater knee extension ($p=0.051$) and external rotation at push-off ($p=0.038$), and greater hip flexion throughout the stride ($p=0.027$) after controlling for speed. Interactions existed between speed and skill level including faster skating speeds were associated with increased plantarflexion at push-off in low calibre participants while there was no relationship in high calibre participants. Skating pattern differences between skill levels provide an indication of ideal joint motion during skating. Players should be encouraged to plantarflex the ankle during push-off, extend and externally rotate the knee during push-off, and increase hip flexion throughout stride.

*Abstract Word Count: 200*


**Key Words:** motion capture, kinematic, skates, joint angle

## Introduction

The International Ice Hockey Federation (IIHF) estimates that over 1.7 million individuals are registered to play ice hockey worldwide (IIHF, 2017). One of the most important skills in ice hockey is forward skating. To assess skating technique, subjective visual analysis of body segment and joint movements is often preferred by coaches to both interpret and communicate training interventions that aim to improve an athlete's performance. Objective evaluation of skating is also possible using instruments such as electro-goniometers, accelerometers, optical motion capture, force transduces, and surface electromyography (Behm, Wahl, Button, Power, & Anderson, 2005; Chang, Turcotte, & Pearsall, 2009; Fortier, Turcotte, & Pearsall, 2014; Lafontaine, 2007; Robert-Lachaine, Turcotte, Dixon, & Pearsall, 2012; Shell et al., 2017; Stetter, Buckeridge, von Tscharner, Nigg, & Nigg, 2016; Stull, Philippon, & LaPrade, 2011). These instruments provide objective data that could be used to assess the impact of skate design and the identification of efficient and effective skating motion.

One approach to identifying kinematic variables that are associated with an effective skating pattern is to compare high and low calibre players. For example, a previous study compared joint angles between high (n=5) and low (n=5) calibre male players while skating on a treadmill (Upjohn, Turcotte, Pearsall, & Loh, 2008). High calibre players had greater ankle plantarflexion and knee extension at propulsion, greater hip flexion at initial contact, and greater knee and ankle sagittal range of motion. Other studies have been completed on ice surfaces (Buckeridge, LeVangie, Stetter, Nigg, & Nigg, 2015; Renaud et al., 2017). Low calibre players (n=9) had greater hip abduction angles at initial contact, although high calibre players (n=9) had greater hip abduction velocities and greater sagittal hip range of motion, during a start task on ice (Buckeridge et al., 2015). Another study, found high calibre players (n=7) achieved faster skating speed by way of higher stride rates and higher vertical centre of mass compared to low calibre players (n=8) during a start task on ice (Renaud et al., 2017). These studies highlight skating patterns that are associated with higher skill level which could be utilised in the instruction of players.

Previous skating studies have summarised joint angle waveforms by identifying discrete values at a particular point in time (e.g. hip flexion at ice contact) (Renaud et al., 2017). These discrete values ignore the temporal component and pattern structure of these waveforms. Other data reduction techniques, such as principal component analysis (PCA), can reduce waveform dimensionality and still consider the temporal component (Deluzio & Astephen, 2007). PCA might be able to identify other pertinent differences between players and deconstruct fundamental movement factors corresponding to high and low skating performance. PCA has been utilised to study some sport activities, such as cutting while running (Landry, McKean, Hubley-Kozey, Stanish, & Deluzio, 2007) and skiing (Gloersen, Myklebust, Hallen, & Federolf, 2018), but has not been applied to skating. In addition, given there is limited objective data on the proper skating technique and limited knowledge of differences between high and low calibre players, quantitative data analysis needs to better tease out relevant movement-to-performance factors. If coaches are to be successful at instructing players, it is important to understand optimal skating mechanics. Therefore, the objective was to compare hip, knee, and ankle joint angles during full stride skating on ice between high and low calibre hockey players using PCA. It was hypothesised that joint angle differences would exist between high and low calibre players during full stride skating. High calibre players would have greater ankle plantarflexion and knee extension at push-off, and greater hip flexion and abduction excursion throughout the stride. Such movements would increase stride length and power output and may explain the higher skating speeds typically demonstrated in high calibre players (Buckeridge et al., 2015; Renaud et al., 2017; Upjohn et al., 2008).

## Methods

### *Participants*

Male hockey players (n=16) between 20 to 30 years of age were recruited for this observational study between November 2014 and January 2015. They could not have had lower extremity surgery within the last year. Participants were classified as high calibre (n=8) or low calibre (n=8). High calibre participants were recruited from the university varsity team and had played at least at the major junior level. Low calibre participants were recruited from local recreational teams and played hockey at levels lower than major junior. The study was conducted with the formal approval of the McGill University Research Ethics Board. Written, informed consent was obtained from participants. Demographic statistics were measured including age, height, weight, and self-reported years of playing experience (Table 1).

Data were collected at the same session as a previous published study that examined skating starts (Renaud et al., 2017). The sample size was thus limited to this previous study. The sample size was low (n=16) because of the cost and technical difficulty collecting on an ice surface.

### *Motion capture data collection*

Forward skating full stride data were collected with a ten camera motion capture system sampled at 240 Hz (Vicon Motion Systems Ltd., Oxford, UK; eight MX3+ cameras, and two T40S cameras) on an indoor ice surface. The approximate capture area was 3 m wide, 6.5 m long, and 1.5 m high. Participants wore tight fitting compression clothing, hockey gloves, helmet, and carried a hockey stick. All participants wore the same skate model (Bauer MX3, Bauer Hockey Ltd., Blainville, Canada), which were not their normal skates. This was done to eliminate any potential effects of skate design and sharpening on skating metrics (Federolf & Nigg, 2012; Federolf & Redmond, 2010). The skates were sharpened by the same technician before each data collection with 3/8 inch (9.53 mm) radius of hollow. Participants were instructed to lace their skates as they normally would for a game.

Twenty-four reflective markers were placed on participants according to a modified Helen-Hayes marker system, as previously described (Collins, Ghoussayni, Ewins, & Kent, 2009; Renaud et al., 2017), including bilaterally over: anterior superior iliac spine, posterior superior iliac spine, lateral mid-thigh (wands), lateral femoral epicondyle, lateral mid-shank (wands), lateral malleolus, first metatarsal heal, third metatarsal head, fifth metatarsal head, and heels. Foot markers were placed on the skates and thus represented approximate anatomical locations. Markers were placed bilaterally on medial femoral epicondyle and medial malleolus during static trials in order to identify knee and ankle centres. The same two researchers applied markers to all participants. These markers were removed during skating.

Participants were allowed a 5 min warm-up on the ice. A static standing trial was then collected with joints in a neutral position. A foot template was used to ensure there was consistent foot position between participants (Collins et al., 2009; Renaud et al., 2017). Next, participants performed skating trials by starting in a hybrid-v stance then skating as fast they could from the goal line to the blue line, a distance of 19.5 m. They entered the capture area after 6.1 m of acceleration. Five trials per participant were captured.

### *Data processing*

Gap filling was completed using Vicon IQ (Version 2.5, Vicon Motion Systems Ltd., Oxford, UK). Marker data were filtered with a low pass, recursive, 4$^{th}$ order Butterworth filter with a cut-off frequency of 6 Hz in order to remove unwanted noise or movement artefact. Knee and ankle centres were identified as the midpoint between markers on these joints. Hip joint centres were identified from anatomic landmarks using previously described regression equations (Schwartz & Rozumalski, 2005). Ankle, knee, and hip angles were calculated about joint co-ordinate systems in the sagittal (positive-flexion/dorsiflexion; negative-extension/plantarflexion), frontal (positive-adduction/inversion; negative-abduction/eversion), and transverse (positive-internal rotation; negative-external rotation) planes (Collins et al., 2009; Wu et al., 2002). Frontal plane knee angles were not considered for further analysis since this motion is limited. Static trial joint angles were subtracted from skating trial joint angles to account for potential offsets due to marker placement. Waveforms were time normalised to 100% of stride using cubic spline interpolation, which was from the first ice contact in the capture area to subsequent ice contact of the same skate. Skate contact events were determined by automatically identifying peak vertical acceleration of the heel markers. This method has been used in gait research (Hreljac & Marshall, 2000). All events were checked manually to confirm accuracy. Average skating speed was determined by taking the derivative of posterior superior iliac spine marker positions and was averaged across each skating trial. Stride length and time were the distance travelled and the time it took, respectively, from ice contact to subsequent ice contact of the same skate. Filtering, angle determination, event detection, and gait speed calculation were performed in Visual3D (Version 5.01, C-Motion Inc., Germantown, USA) while time normalisation was performed in Matlab (version R2012a, MathWorks Inc., Natick, USA).

### *Side selection*

Data were available for both limbs since reflective markers were placed bilaterally. However, the capture area was not large enough to consistently measure complete skate strides from both limbs. For each participant, the limb with the greatest number of trials with complete knee angle data was chosen as the limb of interest, irrespective of limb dominance. When there were an equal number of trials for both sides, the limb was chosen randomly. The left limb was chosen two and three times for high and low calibre participants respectively. The right limb was chosen six and five times for high and low calibre participants respectively. Additionally, since the capture area was not large enough, not all of the five trials collected per participant could be processed. The minimum, maximum, and median number of available trials for processing were determined and are presented in the results.

### ***Principal component analysis***

PCA decreased dimensionality of angle data and it permitted the identification of important waveform characteristics (Deluzio & Astephen, 2007). Separate PCAs were conducted for each angle (ankle, knee, hip) in each plane (sagittal, frontal, transverse) resulting in eight analyses (three for hip and ankle; two for knee). This approach was utilised, as opposed to entering all joint angles in one PCA, because this approach is more sensitive to changes within individual joint angles, which was the primary objective of the current study. In addition, this analysis would allow the identification of specific joint motions associated with a more ideal skating pattern, which could be transferred to a coaching intervention. For each analysis, data were entered into a $n \times m$ matrix ($\mathbf{X}$) where $n$ is the number of trials for every participant and $m$ is the 101 data points over stride cycle. Since individual trials were entered, and not ensemble averages, participants were in each analysis multiple times. This was done to increase matrix size and ensure stable analyses. For the ankle, knee, and hip angles, the matrices sizes were 53x101, 52x101, and 55x101, respectively. The discrepancies between joints were due to missing segments for part of a trial. From the covariance matrix of **X**, eigenvectors were extracted, also named principal components (*PC*). These represent important waveform characteristics such as overall magnitude and shape, timing differences, or difference operators (i.e. differences in the waveform amplitude between different points in time or phases). The amount of variability in each *PC* was indicated by eigenvalues. The first three *PCs* were examined because they often account for the majority of variability. Principal component scores (*PC-scores*) were determined ($PC\text{-}scores=(\mathbf{X}-\bar{\mathbf{X}})*PC$). They represent how closely a waveform matches the *PC* shape. These *PC-scores*, derived from lower extremity joint angles, were used for further statistical testing and were the primary dependent variables. PCA was performed using Matlab (version R2012a, MathWorks Inc., Natick, USA).

### *Statistical analysis*

Descriptive statistics were calculated for group demographics and spatiotemporal variables. Average speed, stride length, and stride time were averaged across all available trials for each participant. These variables were compared between groups using independent t-tests.

Hierarchical linear models were constructed to address the study purpose. Dependent variables were angle *PC-scores* and separate models were constructed for each *PC-score*. Available data at the individual trial level were entered into the models and data were clustered with-in the participants. This allowed for more accurate partitioning of variability (e.g. with-in and between participant variability) compared to if ensemble means were calculated for a joint angle for each participant prior to performing a statistical analysis such as a regression analysis (Tirrell, Rademaker, & Lieber, 2018). In addition, entering individual trials increased the available data entered into the analyses. Two separate model types were constructed, one which

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did not statistically control for skating speed (non-speed model) and another which statistically controlled for speed (speed model). The effect of speed was examined since it was assumed high calibre participants would skate faster and potential relationships could be due to speed, and not group differences. For non-speed models, intercept and trial number were entered in the first step to account for potential effects of fatigue. Next, the group variable (high vs. low calibre) was entered. For speed models, the intercept and trial number were entered in the first step followed by average speed over the trial. Group was entered in the next step, followed by a group x speed interaction. This interaction was only kept if it significantly contributed to the model. Trial number and speed were entered as continuous variables while group (low calibre=0; high calibre=1) was entered as a categorical variable. The -2 log-likelihood (*-2LL*) and critical values for the chi-square statistic were used to assess different stages of model development. The final model regression coefficients (i.e. slope) were reported with 95% confidence intervals with associated $p$ values from the Wald statistic. Statistical significance was set at $p$=0.050. For every model, full maximum-likelihood was chosen, degrees of freedoms were calculated with the Kenward-Roger method, and the covariance structure was variance components (Singer & Willett, 2003; Wang, Xie, & Fisher, 2011). To ensure statistical assumptions were met, the following diagnostics were examined: normality, multicollinearity, linearity, homoscedasticity, and influential cases. SAS Enterprise Guide (version 7.13, Cary, USA) was used to construct the models.

## Results

There were no significant differences between groups for demographic variables except the high calibre group had significantly more playing experience (Table 1). Average speed was not statistically different between groups although it was approaching significance ($p$=0.074) with the high calibre group skating faster (Table 1). There were no significant group differences for stride length and time (Table 1). The knee had the least number of available trials for analysis (Table 2). The minimum number of available trials for a participant was two, the maximum was five, and the median was three.

Group means for the angles are provided in Figure 1-3. An interpretation for each *PC* and the explained variance are provided in Table 3. For all hierarchical linear models, intercept was entered as a random effect, remaining variables were entered as fixed effects, and statistical assumptions were met. Regression coefficients (i.e. slope) are provided in Table 2.

***Ankle results***

Since foot markers were placed on the skates, ankle angles reflect skate motion and not necessarily foot motion. For sagittal ankle angle *PC2-scores*, adding group did not significantly improve the non-speed model (*-2LL* change=2.2, $p$=0.138). For the speed model, adding group did not significantly improve the model (*-2LL* change=0.1, $p$=0.752); however, adding group x speed interaction significantly improved this model (*-2LL* change=6.9, $p$=0.009; Table 2). Higher *PC2-scores* indicated greater change in dorsiflexion during glide (0-40%) to plantarflexion during push-off (50-60% stride) (Figure 4). This interaction demonstrated that the relationship between sagittal ankle angle *PC2-scores* and speed depended on the group. Specifically, higher *PC2-scores* (i.e. greater sagittal ankle excursions) were related to faster speeds in the low calibre group (Figure 5A). There was no relationship between *PC2-scores* and speed in the high calibre group.

For frontal ankle angle *PC1-scores*, adding group significantly improved non-speed (-*2LL* change=20.2, $p$<0.001) and speed (*-2LL* change=24.0, $p$<0.001) models (Table 2). The higher calibre group had higher *PC1-scores*, indicating that they had more ankle inversion during push-off and recovery phases (40-90% stride) (Figure 1B and 4).

For transverse ankle angle *PC3-scores*, adding group did not significantly improve the non-speed model (*-2LL* change=0.8, *p*=0.371). Also, adding group did not significantly improve the speed model (*-2LL* change=0.2, *p*=0.655); however, adding group x speed interaction significantly improved the speed model (*-2LL* change=4.9, *p*=0.027; Table 2). Higher *PC3-scores* indicated greater ankle external rotation excursion from glide/push-off (30-50% stride) to recovery (Figure 4). The interaction demonstrated that for the low calibre group, higher *PC3-scores* were related to faster speeds (Figure 5B). This relationship was in the opposite direction for the high calibre group (Figure 5B).

For the remaining ankle analyses, there were no other significant relationships between group and *PC-scores*.

***Knee results***

For sagittal knee angle *PC3-scores*, adding group significantly improved the non-speed model (*-2LL* change=4.8, *p*=0.028; Table 2). Group approached significance in the speed model (*-2LL* change=3.8, *p*=0.051). The higher calibre group had lower *PC3-scores* indicating greater knee extension during push-off (Figure 2A and 6).

For transverse knee angle *PC2-scores*, adding group significantly improved non-speed (*-2LL* change=4.7, *p*=0.030) and speed (*-2LL* change=4.3, *p*=0.038) models (Table 2). The higher calibre group had lower *PC2-scores* indicating that they had greater external rotation during push-off (Figure 2B and 6).

For remaining knee analyses, there were no other significant relationship between group and *PC-scores*.

### *Hip results*

For sagittal hip angle *PC1-scores*, adding group did not significantly improve the non-speed model (*-2LL* change=2.6, *p*=0.107). However, adding group significantly improved the speed model (*-2LL* change=4.9, *p*=0.027; Table 2). The higher calibre group had higher *PC1-scores* indicating that they had greater hip flexion throughout the stride (Figure 3A and 7).

For sagittal hip angle *PC2-scores*, adding group significantly improved the non-speed model (*-2LL* change=5.0, *p*=0.025; Table 2). However, group was not significant in the speed model (*-2LL* change=1.3, *p*=0.254). *PC2* represents a time shift in the movement from hip extension during push-off to hip flexion during recovery (Figure 7). This movement occurred earlier in stride for the high calibre group since they had lower *PC2-scores* (Figure 3A). Given the differences in non-speed and speed models, this relationship is dependent on skating speed.

For the remaining hip angle analyses, there were no other significant relationship between group and *PC-scores*.

## Discussion and Implications

This is the first study to deconstruct fundamental ice skating mechanics using PCA across the entire skating motion and compare differences in these mechanics between high and low calibre players. Differences in lower extremity joint angles during full stride skating between high and low calibre players were found. These disparities provide insight into skating techniques that may be consistent with improved performance. Joint motions that might lead to improved performance and should be recommended to players and coaches include: 1) increased excursion from ankle dorsiflexion during glide to plantarflexion during push-off, 2) increased ankle inversion at the end of push-off, 3) increased knee extension during push-off, 4) increased knee external rotation during push-off, 5) increased hip flexion during glide, and 6) faster movement from hip extension to flexion during recovery. Recommending these changes to players will greatly depend on their current skating pattern and thus will need to be player specific. However, given the observational design of the study, it is not clear if skating performance will be improved if players incorporate these recommendations. Experimental studies that address potential deficits are required to substantiate the current findings.

### *Sagittal plane*

Consistent with the hypothesis, there were differences in sagittal angles between groups. In the low calibre group, a greater change in dorsiflexion during glide to plantarflexion at push-off was related to faster skating speeds. This relationship was not present in the high calibre group because they had less variability (Figure 5A). A previous study found increased sagittal ankle range of motion in high compared to low calibre players during treadmill skating (Upjohn et al., 2008). Increased dorsiflexion during glide would stretch the gastrocnemius, and this energy could be released during plantarflexion at push-off (stretch-shortening cycle). Additionally, hockey skates have been modified to permit more ankle plantarflexion in attempt to mimic klapskates used in speed skating (Robert-Lachaine et al., 2012). Klapskates, which pivot near the forefoot, permit increased plantarflexion during push-off leading to increased power generation compared to conventional speed skates (Houdijk et al., 2000). Thus, increasing ankle plantarflexion during push-off could potentially generate more power and increase skating speed. At the knee, high calibre participants had increased knee extension at push-off which would also increase power generation (Figure 2A). A similar finding was demonstrated in a previous study (Upjohn et al., 2008). Concerning sagittal hip angles, the high calibre group had greater hip flexion throughout the stride (Figure 3A). Greater hip flexion may enhance stride length during glide and push-off, and improve the stretch-shortening cycle of gluteus maximus.

Also, the high calibre group had a faster recovery of hip flexion (Figure 3A) allowing them to prepare for the next stride cycle, although this finding was dependent on speed. Both of these findings in the hip are novel and have not been previously demonstrated; although high calibre players were previously shown to have greater hip flexion at initial ice contact (Buckeridge et al., 2015; Upjohn et al., 2008). These differences in sagittal angles could indicate that high calibre players are utilising more efficient and effective skating patterns.

***Frontal plane***

In the frontal plane, groups demonstrated eversion during glide and push-off (0-40% stride); however, the high calibre group had increased ankle inversion during the end of push-off and recovery (Figure 1B), which was a novel finding. Perhaps this inversion allows high calibre participants to quickly flick their skate off the ice and back towards the midline, thereby allowing faster recovery times. Contrary to the hypothesis, there were no statistical differences in frontal hip angles between groups; although, a visual difference is noted (Figure 3B) with high calibre participants having increased hip abduction throughout stride. The high variability in the low calibre participants (Figure 3B) and the small sample size likely account for this non-significant finding. This increased abduction in high calibre participants would increase base of support and might improve stability. This could allow high calibre players to better absorb body contact with another player. In contrast, a previous study demonstrated increased hip abduction, measured with an electro-goniometer, during initial contact and push-off in low compared to high calibre players during forward skating on ice (Buckeridge et al., 2015). Further exploration is warranted to determine ideal frontal plane hip motion.

***Transverse plane***

There were significant findings in ankle and knee transverse plane angles. The high calibre group had greater knee external rotation during push-off (Figure 2B). This would place the skate more perpendicular to skating direction allowing the edges to be utilised more effectively and potentially increase horizontal ground reaction force. However, the ideal skate position that would produce the optimal balance between anterior/posterior and medial/lateral forces has not yet been established and too much horizontal force could negatively impact forward skating speed. Also, the direction of the relationship between speed and transverse ankle angle varied between groups (Figure 5B). Within low calibre participants, skating speed was directly related to greater ankle external rotation excursion from glide/push-off to recovery. This relationship was in the opposite direction for the high calibre group. Thus, players might have different strategies to increase skating speed based on skill level, including knee external rotation and ankle external rotation in high and low calibre players respectively. These findings are novel, highlight that the angle of the skate with respect to the ice is an important factor in skating, and players may utilise different mechanisms (e.g. hip, knee, or ankle rotation) to achieve transverse skate rotation. Caution should be taken regarding transverse plane findings as these measures are prone to error from collection issues such as wand marker placement (Kadaba, Ramakrishnan, & Wootten, 1990). However, studies that have utilised similar collection procedures (e.g. foot template, removal of standing offsets) have produced repeatable transverse plane angles during gait (Collins et al., 2009).

### *Limitations*

There are several limitations. The sample size was small and results can only be generalised to male hockey players with similar experience. Motion of the trunk and upper extremities were not captured and would provide additional information. Finally, participants had limited experience with the study skates which likely affected their comfort. A standard skate was chosen to control for the potential effect of skate design. This decision does limit the generalizability of the findings to this particular skate model, and other skate models should be tested.

## Conclusions

In conclusion, skating pattern differences between skill levels provide an indication of the ideal joint motion during skating. Players should be encouraged to plantarflex the ankle during push-off, extend and externally rotate the knee during push-off, and increase hip flexion throughout stride. Additional studies are required to examine if addressing these differences in players will actually improve skating performance.

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Table 1: Means (standard deviation) for the group demographics and spatiotemporal variables.

| Variable | High Calibre (n=8) | Low Calibre (n=8) | *p* value* |
|---|---|---|---|
| Age (y) | 24 (3) | 24 (3) | 0.752 |
| Height (m) | 1.84 (0.06) | 1.79 (0.03) | 0.089 |
| Weight (kg) | 86.8 (5.6) | 81.3 (8.4) | 0.143 |
| Body mass index (kg/m$^2$) | 25.7 (1.3) | 25.2 (2.4) | 0.656 |
| Playing Experience (y) | 19 (4) | 9 (6) | 0.001 |
| Average Speed (m/s) | 6.00 (0.37) | 5.53 (0.59) | 0.074 |
| Stride Length (m) | 3.51 (0.11) | 3.43 (0.33) | 0.192 |
| Stride Time (s) | 0.59 (0.04) | 0.64 (0.09) | 0.894 |

*p value from independent t-test

Table 2: Regression coefficients (i.e. slope) estimates (95% confidence intervals) for non-speed and speed hierarchical linear models.

| Angle (number of available trials) | *PC* | Non-Speed Model Regression Coefficients | Speed Model Regression Coefficients | | |
|---|---|---|---|---|---|
| | | Group* | Speed | Group | Interaction** |
| Sagittal Ankle (53 trials) | 1 | -34.32 (-75.62, 6.98) | -15.61 (-53.44, 22.23) | -26.57 (-71.74, 18.60) | N/A |
| | 2 | 17.32 (-6.41, 41.06) | 41.59 (22.42, 60.77) | 300.22 (83.19, 517.25) | -50.51 (-87.32, -13.71) |
| | 3 | -11.45 (-31.08, 8.19) | -3.84 (-23.67, 15.98) | -9.54 (-31.55, 12.47) | N/A |
| Frontal Ankle (53 trials) | 1 | 64.72 (43.13, 86.32) | 36.19 (23.85, 48.52) | 47.10 (33.64, 60.56) | N/A |
| | 2 | 8.19 (-28.77, 45.15) | -4.54 (-36.58, 27.50) | 10.45 (-30.41, 51.32) | N/A |
| | 3 | 8.85 (-3.02, 20.72) | -6.88 (-18.66, 4.90) | 12.29 (-0.61, 25.19) | N/A |
| Transverse Ankle (53 trials) | 1 | 2.38 (-117.47, 122.23) | 19.70 (-49.17, 88.56) | -7.40 (-128.77, 113.97) | N/A |
| | 2 | 12.83 (-8.61, 34.26) | 23.10 (3.96, 42.25) | 1.36 (-19.66, 22.39) | N/A |
| | 3 | 8.41 (-11.12, 27.93) | 18.80 (0.42, 37.18) | 268.89 (62.31, 475.47) | -44.92 (-79.97, -9.86) |
| Sagittal Knee (52 trials) | 1 | 71.78 (-14.34, 157.90) | 147.55 (104.35, 190.74) | -2.88 (-54.64, 48.87) | N/A |
| | 2 | 0.33 (-49.27, 49.93) | -8.48 (-58.85, 41.90) | 4.52 (-51.31, 60.36) | N/A |
| | 3 | -31.58 (-59.92, -3.25) | -2.21 (-30.70, 26.27) | -30.48 (-62.17, 1.21) | N/A |
| Transverse Knee (52 trials) | 1 | 105.00 (-1717.05, 1927.04) | -15.24 (-74.63, 44.15) | 112.70 (-1603.69, 1829.09) | N/A |
| | 2 | -33.76 (-64.47, -3.05 ) | 4.02 (-26.57, 34.61) | -35.77 (-70.00, -1.55) | N/A |
| | 3 | 18.78 (-10.00, 47.55) | 41.94 (18.80, 65.07) | -2.22 (-28.09, 23.65) | N/A |
| Sagittal Hip (55 trials) | 1 | 51.02 (-13.79, 115.82) | -48.28 (-106.91, 10.05) | 74.74 (8.26, 141.21) | N/A |

| | | | | | |
|---|---|---|---|---|---|
| | 2 | -52.82 (-99.35, -6.29) | -61.05 (-97.64, -24.46) | -22.20 (-62,72, 18.31) | N/A |
| | 3 | 16.92 (-11.30, 45.13) | 23.66 (-3.18, 50.49) | 5.43 (-24.06, 34.92) | N/A |
| Frontal Hip (55 trials) | 1 | -57.86 (-131.27, 15.54) | 1.92 (-60.43, 64.27) | -58.82 (-139.03, 21.38) | N/A |
| | 2 | -14.07 (-39.07, 10.93) | -7.39 (-32.25, 17.48) | -10.43 (-38.40, 17.54) | N/A |
| | 3 | 1.93 (-14.34, 18.19) | -1.58 (-18.44, 15.28) | 2.66 (-15.51, 20.84) | N/A |
| Transverse Hip (55 trials) | 1 | -48.16 (-171.67, 75.35) | -15.08 (-89.53, 59.37) | -40.60 (-167.68, 86.49) | N/A |
| | 2 | 6.03 (-17.99, 30.05) | 1.78 (-23.29, 26.85) | 5.19 (-21.76, 32.13) | N/A |
| | 3 | 3.99 (-19.97, 27.96) | 23.63 (1.61, 45.66) | -7.58 (-31.74, 16.58) | N/A |

*Low calibre participants were coded 0 and high calibre participants as 1.

**Interactions were only included in the model if they were significant.

N/A, not applicable, no interaction existed. *PC*, principal component.

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Table 3: A description of the principal components (*PC*) and the amount of explained variance for each *PC*.

| Variable | *PC* | Description | Higher scores | Variance (%) |
|---|---|---|---|---|
| Sagittal Ankle | 1 | Overall amplitude and shape | Greater overall dorsiflexion amplitude | 52.8 |
| | 2 | Difference operator | Greater difference between glide dorsiflexion and push-off plantarflexion | 20.8 |
| | 3 | Phase shift in timing | Delay in recovery dorsiflexion | 13.7 |
| Frontal Ankle | 1 | Amplitude during push-off and recovery | Greater inversion during these times | 47.3 |
| | 2 | Amplitude during glide, early push-off and late recovery | Greater inversion during these times | 34.1 |
| | 3 | Difference operator | Greater difference in push-off eversion and recovery inversion | 6.6 |
| Transverse Ankle | 1 | Overall amplitude and shape | Greater internal rotation amplitude | 85.6 |
| | 2 | Amplitude during push-off | Greater internal rotation during this time | 4.1 |
| | 3 | Difference operator | Greater excursion in external rotation during glide/push-off to recovery | 3.0 |
| Sagittal Knee | 1 | Overall amplitude and shape | Greater overall flexion amplitude | 62.5 |
| | 2 | Phase shift in timing | Delay in glide/push-off extension and recovery flexion | 23.2 |
| | 3 | Amplitude during push-off | Greater flexion during this time | 8.9 |
| Transverse Knee | 1 | Overall amplitude and shape | Greater overall internal rotation amplitude | 90.3 |
| | 2 | Amplitude during push-off | Greater internal rotation during this time | 3.2 |
| | 3 | Difference operator | Greater difference in late glide/early push-off internal rotation and push-off external rotation | 2.0 |
| Sagittal Hip | 1 | Overall amplitude and shape | Greater overall flexion amplitude | 53.3 |

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| | | | | |
|---|---|---|---|---|
| | 2 | Phase shift in timing | Delay in push-off extension and recovery flexion | 29.5 |
| | 3 | Difference operator | Greater excursion between flexion and extension | 11.4 |
| Frontal Hip | 1 | Overall amplitude and shape | Greater overall adduction | 74.8 |
| | 2 | Phase shift in timing | Delay in recovery adduction | 9.6 |
| | 3 | Difference operator | Greater difference in push-off abduction and recovery adduction | 6.6 |
| Transverse Hip | 1 | Overall amplitude and shape | Greater overall internal rotation | 83.1 |
| | 2 | Difference operator | Greater excursion from internal to external rotation during glide/push-off | 6.1 |
| | 3 | Amplitude during push-off | Greater internal rotation during this time | 4.3 |

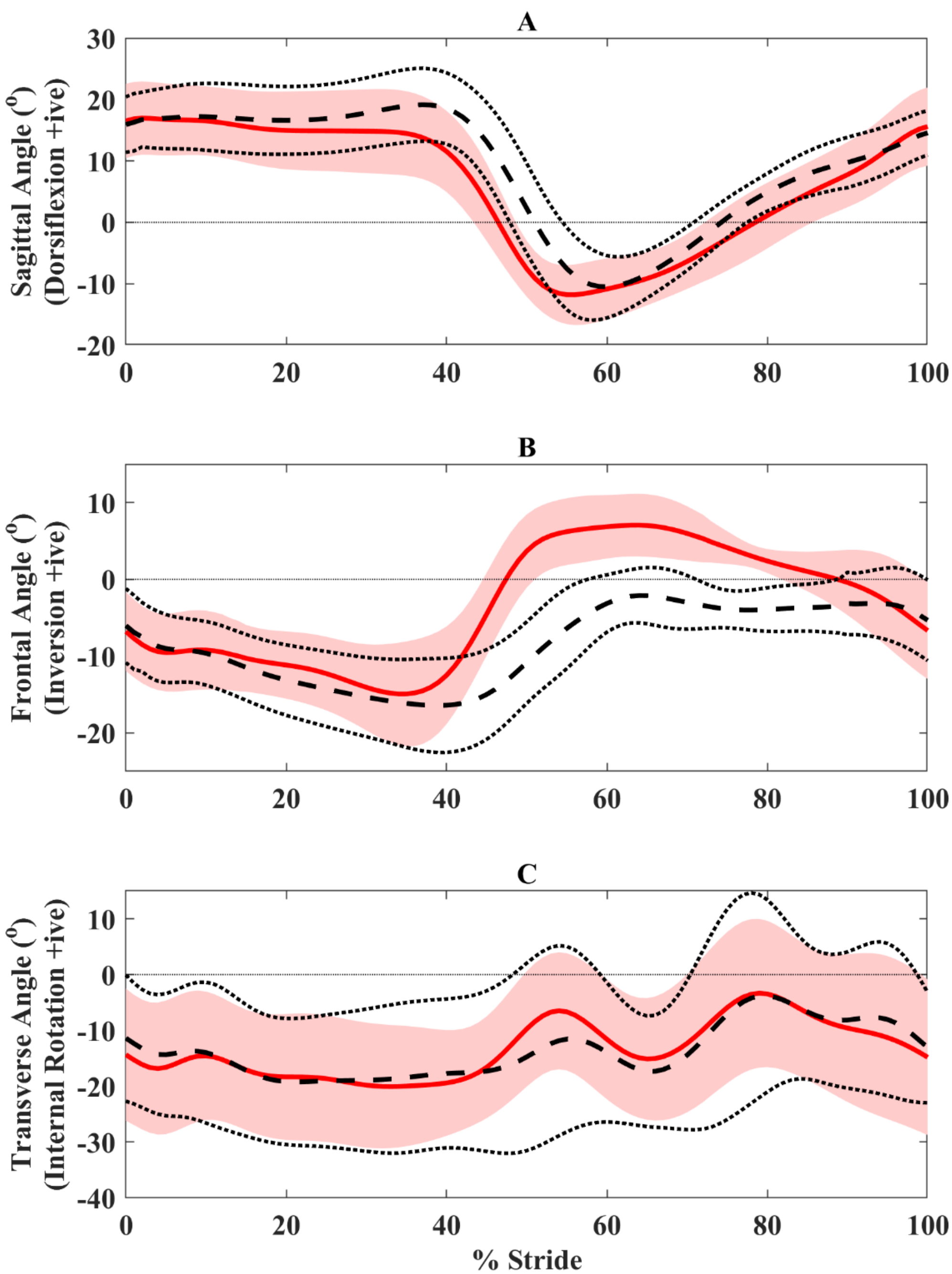


Figure 1. Group means for ankle angles in the (A) sagittal, (B) frontal, and (C) transverse planes during a full stride for high calibre (red, solid lines) and low calibre (black, dashed lines) groups. The pink shaded area represents one standard deviation for the high calibre group and the dotted lines represent one standard deviation for the low calibre group. Dorsiflexion (sagittal), inversion (frontal), and internal rotation (transverse) represent positive values. Figures will appear as greyscale in print editions. Colour figures are available online.

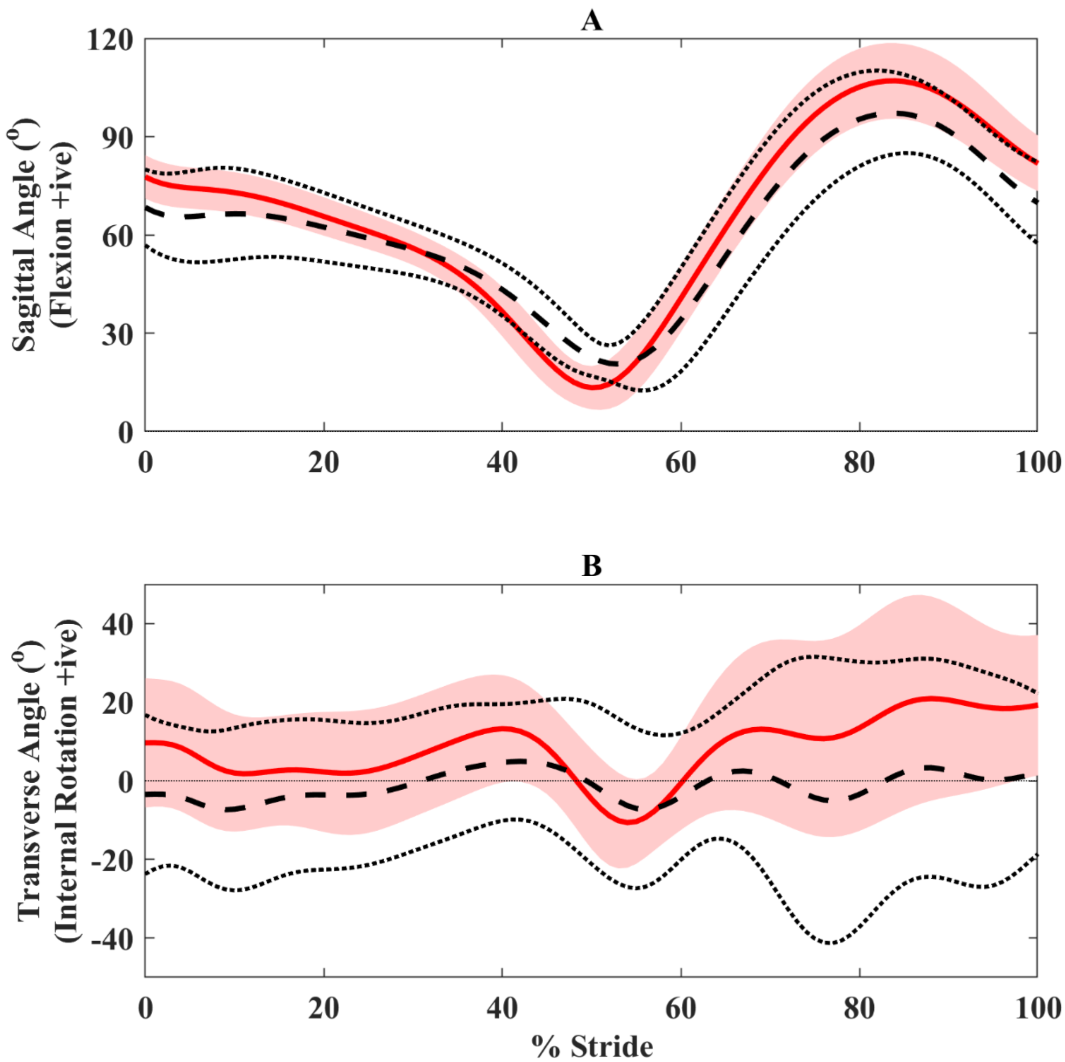


Figure 2. Group means for knee angles in the (A) sagittal and (B) transverse planes during a full stride for high calibre (red, solid lines) and low calibre (black, dashed lines) groups. The pink shaded area represents one standard deviation for the high calibre group and the dotted lines represent one standard deviation for the low calibre group. Flexion (sagittal) and internal rotation (transverse) represent positive values. Figures will appear as greyscale in print editions. Colour figures are available online.

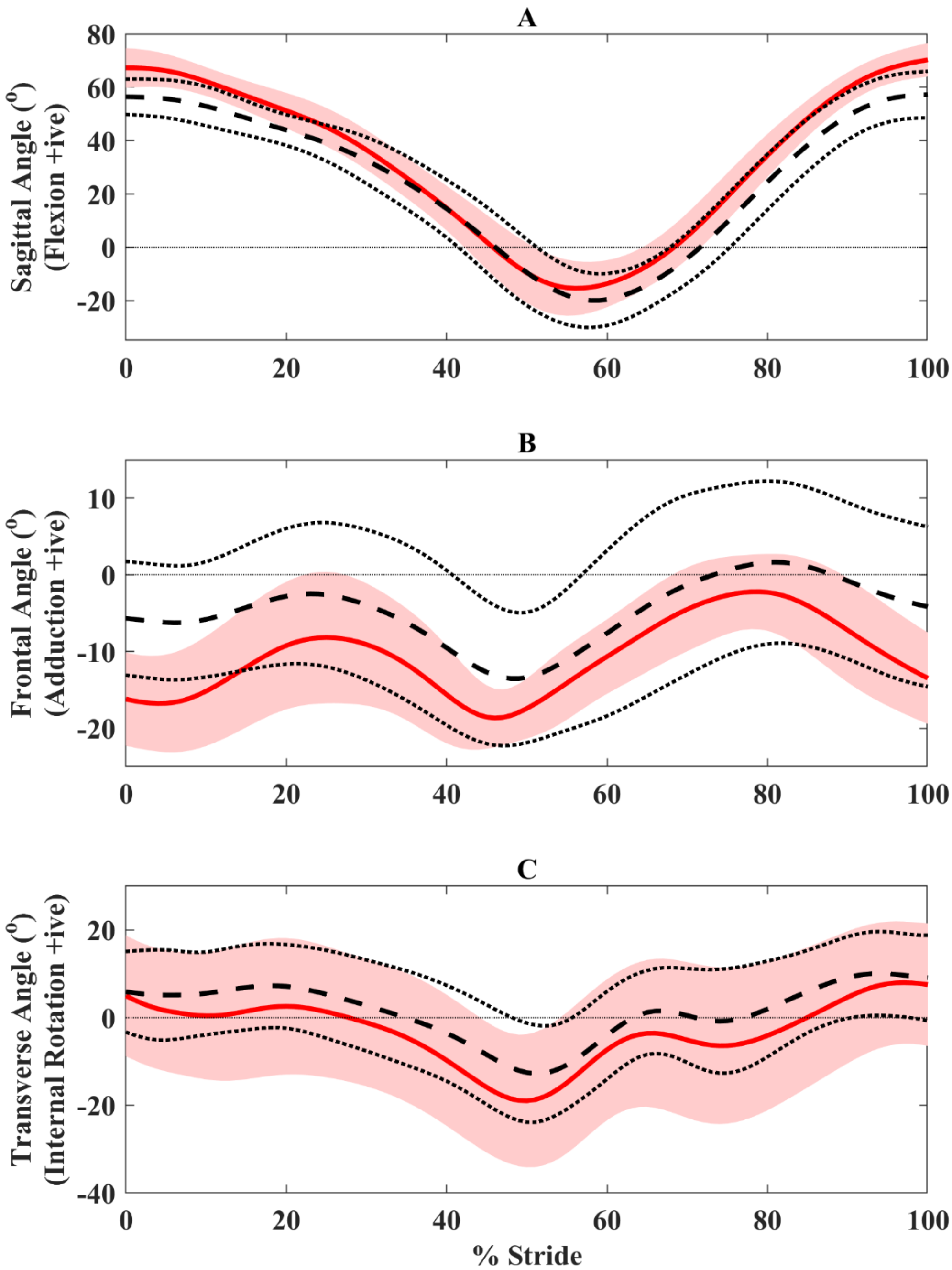


Figure 3. Group means for hip angles in the (A) sagittal, (B) frontal, and (C) transverse planes during a full stride for high calibre (red, solid lines) and low calibre (black, dashed lines) groups. The pink shaded area represents one standard deviation for the high calibre group and the dotted lines represent one standard deviation for the low calibre group. Flexion (sagittal), adduction (frontal), and internal rotation (transverse) represent positive values. Figures will appear as greyscale in print editions. Colour figures are available online.

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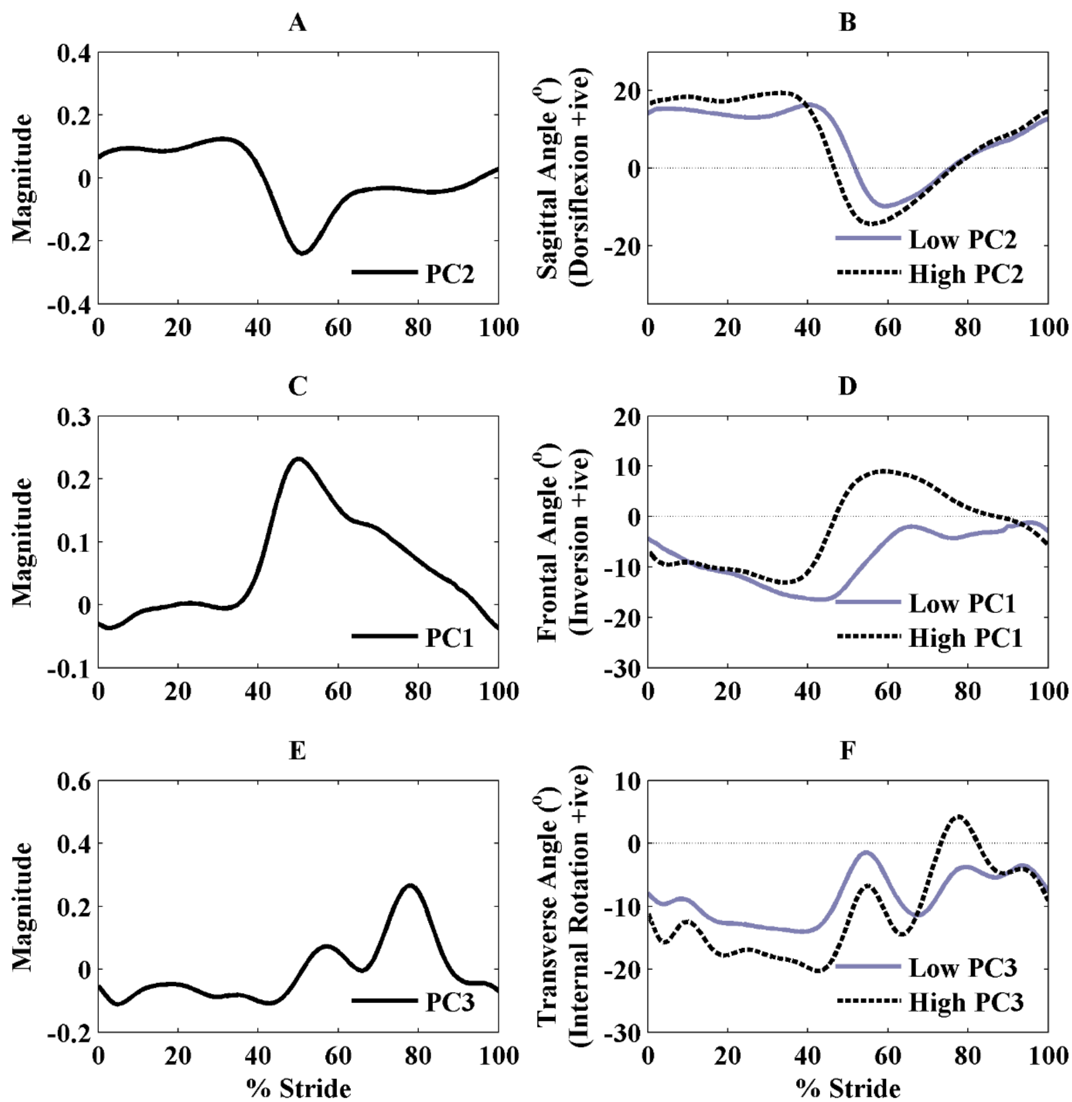


Figure 4. Principal components (*PC*) for the ankle angles. (A) Sagittal angle *PC2* and (B) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures the difference between glide dorsiflexion and push-off plantarflexion. (C) Frontal angle *PC1* and (D) a subset of participants that had high and low *PC1-scores* indicate that this *PC* captures inversion amplitude during push-off and recovery. (E) Transverse angle *PC3* and (F) a subset of participants that had high and low *PC3-scores* indicate that this *PC* captures external rotation excursion during glide/push-off to recovery.

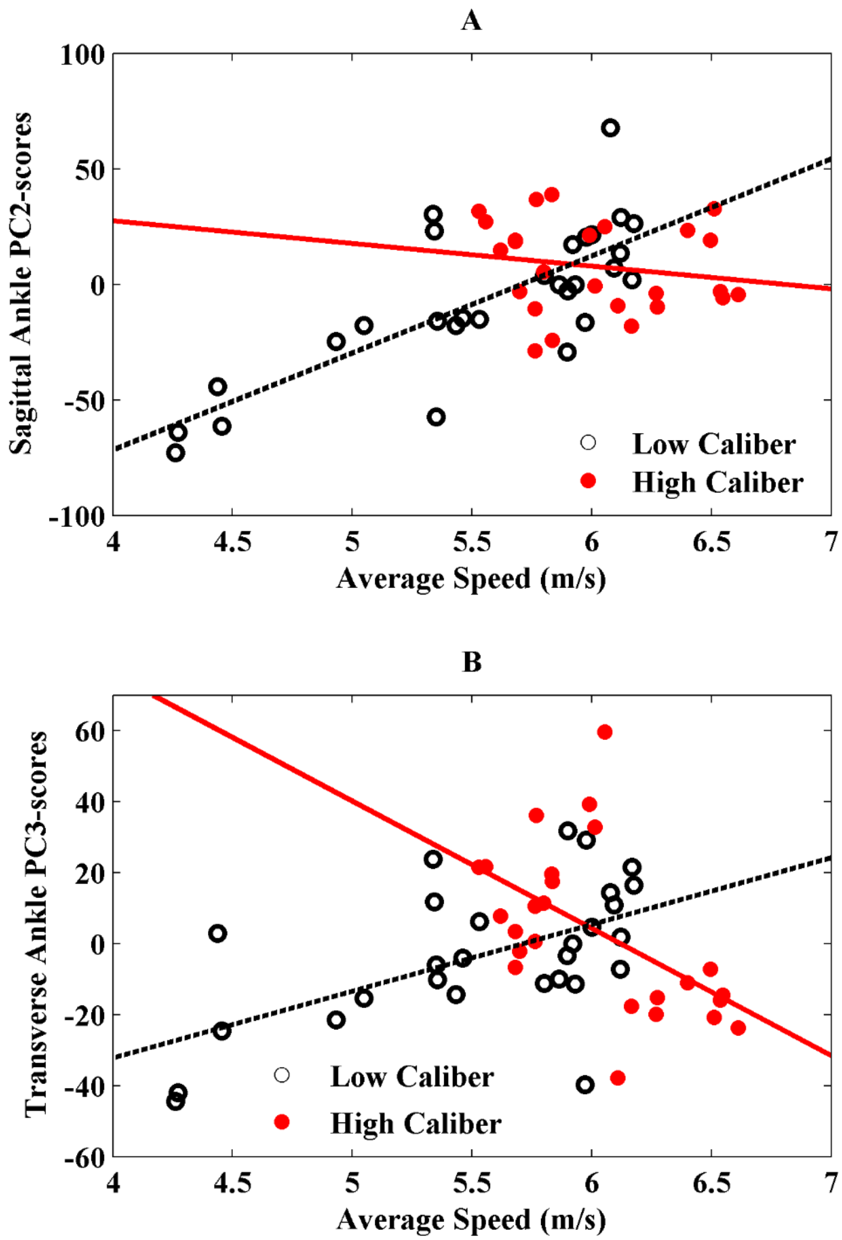


Figure 5. The relationship between (A) average speed with sagittal plane ankle principal component 2 scores (*PC2-scores*) for high (r=-0.17) and low (r=0.77) calibre participants. The relationship between (B) average speed with transverse plane ankle *PC3-scores* for high (r=-0.54) and low (r=0.57) calibre participants. High calibre participants are represented by red, filled dots and low calibre participants by black, unfilled dots. The lines of best fit for the high (red, solid) and low (black, dashed) calibre groups are also represented. Figures will appear as greyscale in print editions. Colour figures are available online.

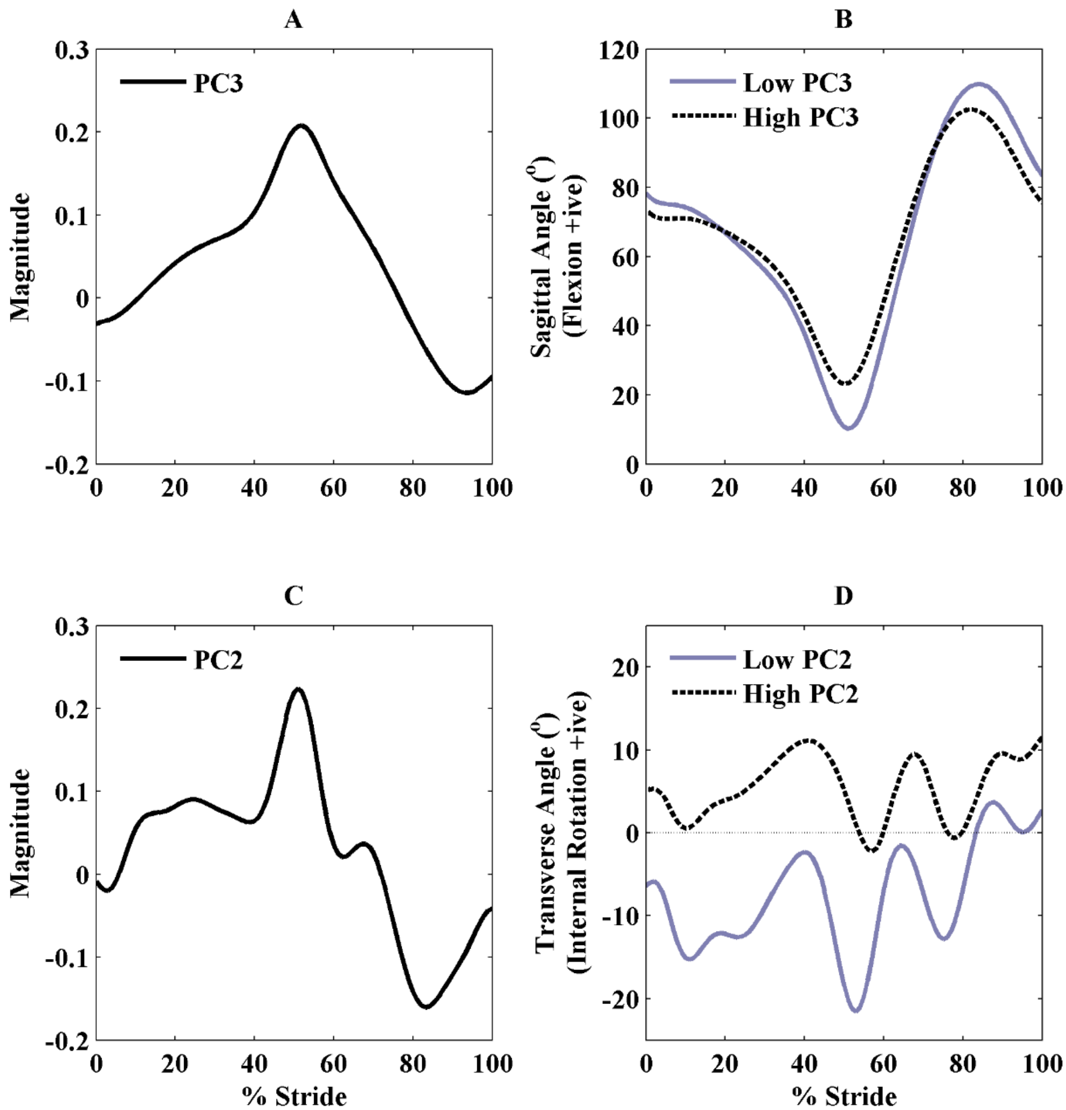


Figure 6. Principal components (*PC*) for the knee angles. (A) Sagittal angle *PC3* and (B) a subset of participants that had high and low *PC3-scores* indicate that this *PC* captures knee flexion amplitude during push-off. (C) Transverse angle *PC2* and (D) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures internal rotation amplitude during push-off.

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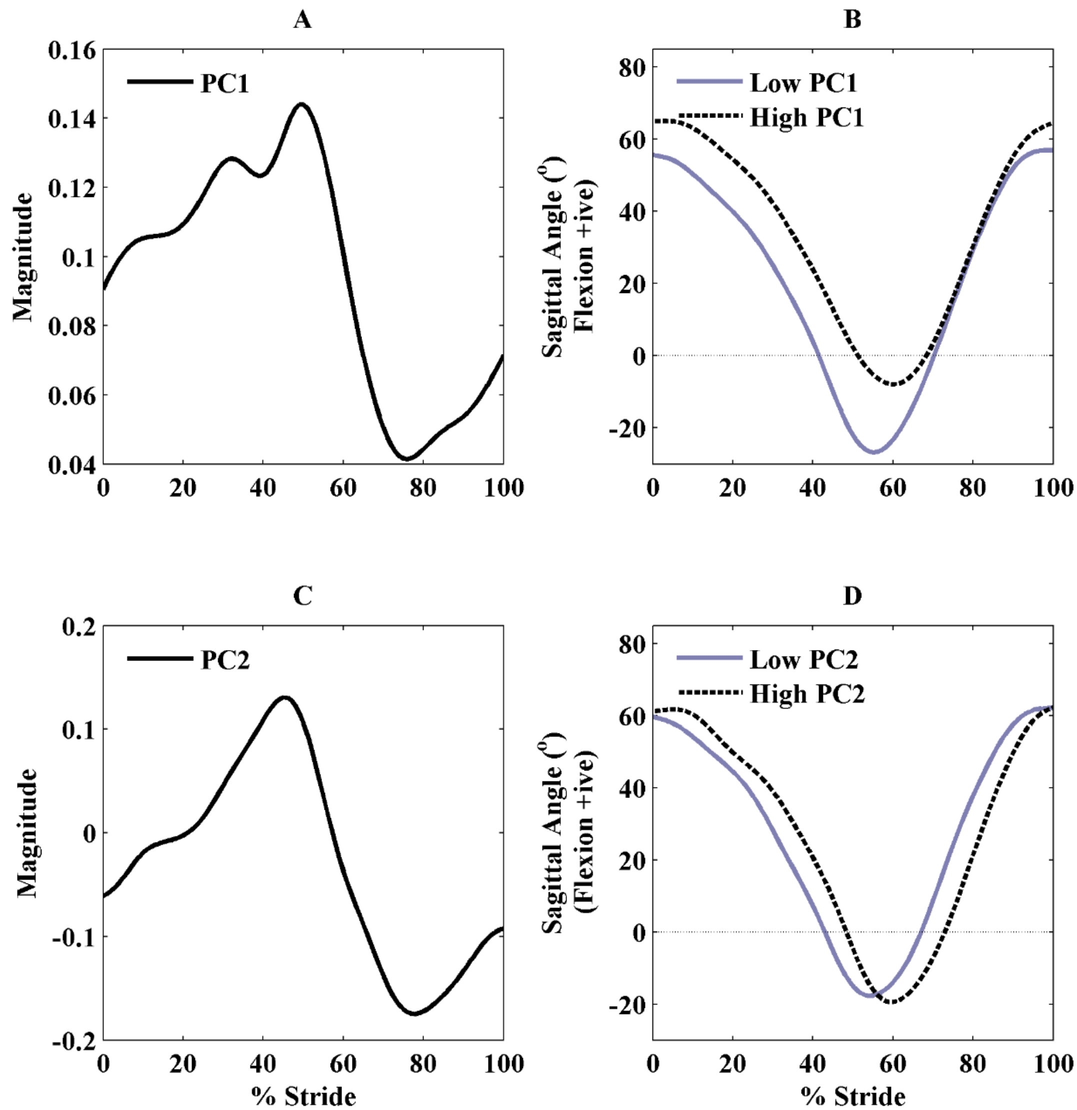


Figure 7. Principal components (*PC*) for the hip angles. (A) Sagittal angle *PC1* and (B) a subset of participants that had high and low *PC1-scores* indicate that this *PC* captures hip flexion amplitude throughout stride. (C) Sagittal angle *PC2* and (D) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures a delay in hip extension during push-off and hip flexion during recovery.

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