Differences in inter-segment coordination between high- and low-calibre ice hockey players during forward skating

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The objective was to compare lower extremity inter-segment coordination between high-calibre and low-calibre ice hockey players during forward full stride skating. A 10-camera Vicon motion capture system collected kinematic data on male high-calibre (n=8) and low-calibre (n=8) participants. Continuous relative phase (CRP) was calculated for shank-*sagittal*/thigh-*sagittal*, shank-s*agittal*/thigh-*frontal*, and foot-*sagittal*/shank-*sagittal* segment pairs. Principal component analysis (PCA) was used to extract features of greatest variability of the CRP and hierarchical linear model investigated relationships between principal components and skill level. High-calibre players demonstrated more out-of-phase coordination (higher CRP) of shank-*sagittal/*thigh-*sagittal* throughout glide/push-off (p = 0.011) as well as a delay in the transition to more in-phase coordination during early recovery phase (p = 0.014). For shank-*sagittal*/thigh-*frontal* (p = 0.013), high-calibre players had more out-of-phase coordination throughout the entire stride. High-calibre players were also associated with an earlier transition to more out-of-phase coordination of the foot-*sagittal/*shank-*sagittal* during push-off (p = 0.007) and a smaller difference in CRP between mid-glide/early recovery (p = 0.016). Utilising more out-of-phase modes of coordination may allow players to more easily adjust to optimal modes of coordination throughout skating strides. Skating drills incorporating varying speed, directionality, and external stimuli may encourage the development of more optimal coordination during skating.

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Introduction

Ice hockey is one of the most popular team sports with over 1.7 million registered players in more than 70 countries during the 2017/2018 season (International Ice Hockey Federation [IIHF], 2018). Biomechanical analysis of ice hockey tasks such as measures of player's body kinematic patterns can highlight elements related to optimal technique and performance. For example, a whole-body kinematic analysis of hockey players' wrist shots has been used to identify movement factors affecting shooting accuracy (Michaud-Paquette, Magee, Pearsall, & Turcotte, 2011), while kinematic studies of forward skating starts have found specific hip, knee, and ankle joint movement differences between males and females (Budarick et al., 2018; Shell et al., 2017). Hence, kinematic analysis, as a supplementary evaluation tool, can yield relevant information to guide coaches and trainers in providing the most appropriate training techniques for their athletes. Additionally, identifying factors governing the locomotion of skating can reveal important information about coordination (Krasovsky & Levin, 2010). As skating is such an integral component of ice hockey, establishing an in-depth understanding of this task is warranted.

Differences in high- and low-calibre hockey players have been evaluated in previous studies to establish what characteristics of skating may lead to improved performance. For example, in a study of skating starts, high-calibre players' quicker start times corresponded with kinematic measures of higher lateral accelerations, higher stride rates, and shorter skate contact time during the first four running steps compared to low-calibre players, even though both groups had similar lower body strength (Renaud et al., 2017). Similarly, in another study by Buckeridge, LeVangie, Stetter, Nigg, and Nigg (2015), they identified that high-calibre skaters have an overall greater range of motion (ROM) of the hip and higher knee extension velocity during propulsion, both thought to contribute to a more effective push-off and increased skating speed. Lower body joint angles of high- and low-calibre players during full stride forward skating were compared on both a skating treadmill and regular ice. In both conditions, high-calibre players showed greater hip flexion throughout stride, and greater knee extension, external rotation, and ankle inversion during push off (Robbins, Renaud, & Pearsall, 2018; Upjohn, Turcotte, Pearsall, & Loh, 2008). These differences between skill levels offer insight into a more effective skating technique, but do not consider the coordination between lower limb segments.

Skating, much like walking or running, is a complex, dynamic movement which requires considerable coordination (Longworth, Chlosta, & Foucher, 2018). Inter-segment coordination can be defined as the relationship and relative timing between different body segments throughout a task (Krasovsky & Levin, 2010). One way to quantify coordination is by using continuous relative phase (CRP), which allows the relation between body segments to be quantified by constructing and comparing phase planes of each respective segment based on kinematic data (Eggleston, Landers, Bates, Nagelhout, & Dufek, 2018; Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2013). Previous research has used CRP to evaluate coordination in a variety of sports providing a wide range of insight. In distance running, out-of-phase coordination has been associated with transitions throughout the gait cycle, and it has been suggested that this coupling pattern may allow for an easier and faster switch to a new coupling pattern in response to perturbations (Dierks & Davis, 2007). Seifert, Leblanc, Chollet, and Delignières (2010) compared inter-limb coordination of recreational swimmers to competitive swimmers and found that recreational swimmers used largely in-phase elbow-knee coordination. Alternatively, a study on coordination and skill level in gymnastics longswing identified that elite gymnasts utilised more in-phase hip-shoulder coordination while successful novices tended to demonstrate more out-of-phase coordination (Williams, Irwin, Kerwin, Hamill, Van Emmerik, & Newell, 2016). Also, stronger attraction to in-phase and anti-phase patterns (more absolute coordination rather than more transitional out-of-phase patterns) may be assumed in cross-country skiing than during walking (Cignetti, Schena, Zanone, & Rouard, 2009). These discrepancies in coordination suggest that the use of in-phase or out-of-phase coordination within a movement is highly task-specific, therefore highlighting the need to identify coordination patterns in forward skating and gain deeper understanding of the fundamental elements that define high-level athletic performance.

Although the mechanics of forward skating between high- and low-calibre ice hockey players have been studied previously, no study has assessed inter-segment coordination in skating which may have implications for more efficient and effective movement patterns. Thus, the objective of this study was to compare lower extremity inter-segment coordination between high- and low-calibre ice hockey players during forward full stride skating. Lower extremity body segments included shank versus thigh in the sagittal plane (shank-*sagittal/*thigh-*sagittal*); shank in the sagittal versus thigh in the frontal plane (shank-*sagittal/*thigh-*frontal*); and foot versus shank in the sagittal plane (foot-*sagittal*/shank-*sagittal*). It was hypothesised that high-calibre players would demonstrate more out-of-phase movement as this mode of coordination may allow for an easier and faster switch to a new coupling pattern and it has been suggested that a flexible coupling pattern is associated with high-standard performance in sprinting (Bradshaw et al, 2007) which bears similarities to forward skating.

Methods

Participants

Sixteen male ice hockey players participated in this study and were classified as high or low-calibre (Table 1). High-calibre players (n=8) had played at the major junior level or higher and were recruited from the university varsity team. Low-calibre players (n=8) had played hockey at a level lower than major junior and were recruited from local teams. Players who had experienced major lower limb injuries within the year prior to data collection were excluded. Data collection took place from November 2014 to January 2015 alongside previously published studies focusing on joint angles during skating starts (Renaud, et al., 2017) and full stride skating (Robbins, et al., 2018). Due to the technical difficulty and cost of collecting data on an ice surface, sample size was limited. Approval from the McGill University Research Ethics Board was obtained, and all players provided written informed consent prior to participation.

Data Collection

Participant age, height, mass, and self-reported playing experience in years were recorded. A 10-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK; 8 MX3+ cameras, 2 T40S cameras) was used to collect forward skating data on an indoor ice surface. Data were sampled at a rate of 240 Hz and the system was calibrated prior to each session. The same two researchers attached 24 passive retro-reflective markers to each player following a modified Helen Hayes marker set-up, as previously described (Collins, Ghoussayni, Ewins, & Kent, 2009; Robbins, et al., 2018). All players wore Bauer MX3 skates with standard boots, which they were told to lace as they would for a game. Skate blades were sharpened by the same technician before every data collection session to a 3/8-inch hollow with a 9.5 radius. In addition to test skates, all players wore compression clothing, a helmet, hockey gloves, and were given a hockey stick to carry while skating to replicate game-situation skating. Players were allotted a 5-minute warm-up period on the ice outside of the capture area. Using a foot template to ensure consistent foot placement between participants, a static standing trial was collected with the joints in a neutral position (Robbins, et al., 2018). Five trials of maximum effort forward skating starting in a hybrid-v stance were captured per participant (Renaud, et al., 2017). Of the total 19.5 m goal line to blue line skating area, participants had the first 6.1 m to accelerate prior to entering the capture area.

Data Processing

Similar to Robbins, et al. (2018), marker data were filtered with a low pass, recursive, 4th order Butterworth filter with a cut-off frequency of 6 Hz to remove unwanted noise or movement artefact. Gap filling was completed using Vicon IQ (Version 2.5, Vicon Motion Systems Ltd., Oxford, UK). Thigh, shank, and foot segment angles were calculated about the global coordinate system and derived from YXZ Cardan angles with the following ordered rotations: flexion, abduction, and rotation. Skate contact (i.e. initial ice contact) events were determined by automatic identification of peak vertical acceleration of the heel markers and manually checked to confirm accuracy (Hreljac & Marshall, 2000; Robbins, et al., 2018). The derivative of the posterior superior iliac spine marker positions was used to determine skating speed and was averaged across each skating trial; peak speed for each trial was also determined. Visual3D (Version 5.01, C-Motion Inc., Germantown, USA) was used for filtering, segment angle determination, event detection, and skating speed calculations. Skating stride can be divided into two main phases: support phase where the leg is in contact with the ice, and swing phase where the leg is off the ice taking the next step. Support phase consists of glide (0 to ~40% of the stride cycle) and push-off (~40-60% stride cycle), while swing phase constitutes recovery (~60-100% stride cycle).

Due to limited capture area, complete skate strides were not able to be consistently measured on both sides. Although bilateral marker placement meant data were available for both limbs, the limb with the greatest number of strides with complete segment data was chosen as the limb of interest. If there were an equal number of strides for both sides, the limb was chosen at random without regard for limb dominance. For high-calibre participants the left limb was chosen twice and the right limb was chosen six times. For low-calibre participants, the left limb was chosen three times and the right limb was chosen five times. Each participant had two to five trials for each segment pair (n = 51 for each pairing). For shank-*sagittal*/thigh-*sagittal* and shank-*sagittal*/thigh-*frontal* pairings the high-calibre group had 28 total trials and for foot-*sagittal*/shank-*sagittal* the high-calibre group had 27 total trials.

Continuous Relative Phase

Phase angles were computed for the foot, shank, and thigh using the Hilbert transform approach. The Hilbert transform allows for a clear assessment of the phase difference through the transformation of a real signal into a complex, analytic signal (Ippersiel, Robbins, & Preuss, 2018; Lamb & Stöckl, 2014). A double reflection method was employed to pad the signal to address issues with data distortion associated with Hilbert transform (Ippersiel, Preuss, & Robbins, 2019). Next, CRP was calculated by determining the absolute difference in the phase angles between body segments (proximal minus distal) in specific planes (Burgess-Limerick, Abernethy, & Neal, 1993) including shank versus thigh in the sagittal plane (shank-*sagittal/*thigh-*sagittal*); shank in the sagittal versus thigh in the frontal plane (shank-*sagittal/*thigh-*frontal*); and foot versus shank in the sagittal plane (foot-*sagittal*/shank-*sagittal*). These segments generally produce the largest amplitudes in those specific directions during skating. A value of 0 degrees indicates the segments are moving completely in-phase with one another (e.g. windshield wipers moving side to side together), while 180 degrees indicates the segments are moving completely anti-phase (e.g. windshield wipers rotating to the centre at the same time). Values closer to 0 or 180 may be relatively in-phase or anti-phase, respectively (Oullier, Bardy, Stoffregen, & Bootsma, 2002). Cubic spline interpolation was used to normalise CRP waveforms to 100% of stride from first ice contact within the capture area to the successive ice contact of the same skate. CRP calculations were performed using Matlab (version R2018a, MathWorks Inc., Natick, USA).

Statistical Analysis

Descriptive statistics were calculated for group demographics, average speed, and peak speed. Independent t-tests were used to compare these variables between high- and low-calibre groups.

Principal Component Analysis

Separate Principal Component Analyses (PCA) were conducted on the CRP waveforms for each segment pair (shank-*sagittal*/thigh-*sagittal*; shank-*sagittal*/thigh-*frontal*; foot-*sagittal*/shank-*sagittal*). This analysis was used to extract important characteristics from the CRP waveforms and summarise the most important information in the data (Deluzio & Astephen, 2007). Data were entered into a n by p matrix ($\mathbf{X}$) where n is the number of trials for all participants and p is the 101 data points over the stride cycle. Matrices sizes for all three segment pairs were 51x101. Eigenvectors, also called principal components (PC), which describe characteristics of the waveforms (e.g. amplitude, time shift), were extracted from the covariance matrix and eigenvalues indicated the amount of variation in the data explained by each eigenvector. Since the first few eigenvectors tend to explain the majority of the variation in the data, the first three eigenvectors were analysed. *PC-scores* (*PC-scores* = ($\mathbf{X}$-$\bar{\mathbf{X}}$)*eigenvectors) were determined to represent the extent to which a waveform matches the eigenvector shape/waveform characteristics and were used in statistical analyses. Eigenvectors will henceforth be referred to as PC. PCA was performed using Matlab (version R2018a, MathWorks Inc., Natick, USA).

Hierarchical Linear Model

Hierarchical linear models (HLM) were used to address the study objectives; HLM allows for an uneven number of observations between players by accounting for variability within a participant. Separate models were constructed for each *PC-score*, which were the dependent variables. Individual trials clustered with-in participants allowed the variability to be partitioned both within and between participants (Tirrell, Rademaker, & Lieber, 2018). For each analysis, two separate models were constructed: a speed model which statistically controlled for speed, and a non-speed model which did not. This was done in order to account for differences that may have been due to skating speed rather than high- or low-calibre group distinction. For the non-speed model, the intercept and trial number were entered in the first step, and group was entered in the second step (categorical – high-calibre = 1; low-calibre = 0). The speed model incorporated trial number and intercept (continuous) into the first step, followed by the average speed over the trial. Group was entered in the third step followed by a group x speed interaction. The interaction term was only maintained in the model if it statistically significantly contributed to the model. Different stages of model development were evaluated using a – 2 log-likelihood and critical values for chi-square statistic. Slope coefficients were also examined and reported with 95% confidence intervals with associated *p* values from the Wald statistic. Full-maximum likelihood was chosen for every model. Statistical significance was set at $p < 0.05$. All statistical analyses were conducted using SPSS Statistics (version 24.0, IBM Corp, Armonk, USA).

Results

Demographic variables were not significantly different between groups with the exception of playing experience which was significantly greater for the high-calibre group (Table 1). Peak speed was significantly greater for high-calibre players (p = 0.043), though average speed between groups was only approaching statistical significance (p = 0.064). Regression coefficients (i.e. slope) are provided in Table 2. Interpretations and the explained variance for each *PC-score* are provided in Table 3. CRP group means for each segment pair are shown in Figure 1.

Shank-sagittal versus Thigh-sagittal

For shank-*sagittal*/thigh-*sagittal PC1-scores*, adding group significantly improved the non-speed model (*-2LL* change = 9.3, p = 0.002). Adding group also significantly improved the speed model (*-2LL* change = 6.4, p = 0.011), however, adding the group x speed interaction did not improve the model (*-2LL* change = 0.6, p = 0.446), demonstrating that the relationship between *PC-scores* was related to skill level (group). The high-calibre group had higher *PC1-scores*, which indicated they had more out-of-phase coordination throughout the glide and push-off phases of skating (Figure 2).

For shank-*sagittal*/thigh-*sagittal PC2-scores*, adding group to the non-speed model did not significantly improve the model (*-2LL* change = 0 .6, p = 0.452), though adding group to the speed model did cause a significant improvement (*-2LL* change = 6.1, p = 0.014) signifying that the relationship between *PC-scores* was related to skill level. This *PC2* represented a time delay of the CRP decrease during push-off/early recovery (Figure 2). The high calibre group had higher *PC2-scores* which indicated a delay in the transition to more in-phase coordination during this time.

For remaining shank-*sagittal*/thigh-*sagittal* analyses, there were no other significant relationships between group and *PC-scores*.

Shank-sagittal versus Thigh-frontal

For shank-*sagittal*/thigh-*frontal PC1-scores*, the relationship between *PC*-scores was dependent upon skill level, as adding group significantly improved both the non-speed (-*2LL* change = 4.1, p = 0.042) and speed (-*2LL* change = 6.2, p = 0.013) models. The high-calibre group was associated with higher *PC1-scores*, which indicated they were more out-of-phase for shank-*sagittal*/thigh-*frontal* coordination throughout the stride (Figure 3).

For shank-*sagittal*/thigh-*frontal PC2-scores*, adding group did not significantly improve the non-speed model (-*2LL* change = 0.9, p = 0.347). Adding group approached significance in the speed model (-*2LL* change = 3.7, p = 0.056) while adding group x speed interaction significantly improved this model (-*2LL* change = 8.1, p = 0.004; Table 2), demonstrating that the relationship between shank-*sagittal*/thigh-*frontal PC2-scores* and speed depended on the group. Higher *PC2-scores* indicated a greater change in CRP from glide to recovery (Figure 3). In the low-calibre group, higher *PC2-scores* were also related to faster skating speeds, demonstrating that faster skaters were more out-of-phase during the recovery phase (Figure 4). This relationship did not exist for the high-calibre group.

For remaining shank-*sagittal*/thigh-*frontal* analyses, there were no other significant relationships between group and *PC-scores*.

Foot-sagittal versus Shank-sagittal

For foot-*sagittal*/shank-*sagittal PC2-scores*, adding group to the non-speed model did not significantly improve the model (*-2LL* change = 1.2, p = 0.271). Adding group significantly improved the speed model (*-2LL* change = 7.4, p = 0.007) denoting that *PC-scores* were dependent on skill level. This *PC2* represented a time delay in the increase in the CRP during push-off/early recovery (Figure 5). High-calibre players had higher *PC2-scores* which indicated an earlier increase in CRP (more out-of-phase) during push-off/early recovery.

For foot-*sagittal*/shank-*sagittal PC3-scores*, the non-speed model was significantly improved by adding group (*-2LL* change = 5.9, p = 0.016), though the speed model was not (*-2LL* change = 1.9, p = 0.169). Higher *PC3-scores* indicated a greater change in CRP from mid-glide to early recovery (Figure 5). The high-calibre group was related to lower *PC3-scores*, meaning they had a smaller difference in CRP between these times. The differences in the non-speed and speed models demonstrate that this relationship is dependent upon skating speed.

For remaining foot-*sagittal*/shank-*sagittal* analyses, there were no other significant relationships between group and *PC-scores*.

Discussion and Implications

This study was the first to compare lower extremity inter-segment coordination between high- and low-calibre ice hockey players during forward full stride skating. The results largely support the hypothesis that, throughout forward full stride skating, high-calibre players demonstrate less in-phase coordination patterns in thigh/shank and shank/foot segment pairs. Greater peak speeds in the high-calibre group could be attributed to coordination differences with out-of-phase coordination being a more effective mode of coordination. Having lower extremity segments be out-of-phase with one another results in more efficient strides as this may allow for better use of the forces present in the system.

Shank versus Thigh

High-calibre players were associated with more out-of-phase coordination, represented by higher CRP, throughout the entire stride (shank-*sagittal*/thigh-*frontal*) and throughout glide and push-off (shank-*sagittal*/thigh-*sagittal*). More out-of-phase coordination, which is considered more variable, may allow players to switch more easily between modes of coordination (Dierks & Davis, 2007). This may mean that players will be more readily able to adjust to outside forces, such as changes in the ice surface or contact with other players, by altering their mode of coordination to one more optimal for their needs. Additionally, high-calibre players had a delay in the transition to a more in-phase mode of coordination for shank-*sagittal*/thigh-*sagittal* (*PC2*) during the early recovery phase and thus remained out-of-phase for longer. More time spent out-of-phase may promote a more restful recovery phase for high calibre players by taking advantage of the forces generated (Temprado, Della-Grasta, Farrell, & Laurent, 1997).

In the low-calibre group, faster skating speeds were associated with more out-of-phase coordination of shank-*sagittal/*thigh-*frontal* during recovery. More out-of-phase coordination during recovery may be related to faster movement from hip extension during push-off to hip flexion during recovery, which has been associated with faster skating speeds (Robbins, et al., 2018).

Foot versus Shank

High-calibre players were associated with an earlier transition to a more out-of-phase mode of coordination (increase in CRP) during push-off for foot-*sagittal*/shank-*sagittal* segments. A more out-of-phase mode of coordination may be optimal for push-off to account for and adapt to changes in ground reaction force and friction as the player pushes against the ice. High-calibre players were also associated with a smaller change in CRP during mid-glide to early recovery. This is likely due to having more out-of-phase coordination (higher CRP) during glide, meaning high-calibre athletes remained more out-of-phase over this time. Similar to shank-*sagittal*/thigh-*sagittal* coordination, operating in a more out-of-phase mode of coordination may allow players to more easily adjust to changes in the ice surface or other outside forces. The overall CRP for foot-*sagittal*/shank-*sagittal* segments is more in-phase throughout the stride than the other segment pairings (Figure 3). An increased need for stability at the foot and shank during skating may dictate that an overall more in-phase mode of coordination for this segment pairing is more advantageous than at the shank/thigh.

Implications

High-calibre players tend to use a more out-of-phase mode of coordination which, we speculate, may allow them to more easily alter their coordination. Because high-calibre players have significantly more experience than low-calibre players (Table 1), this has likely allowed them to create and develop an adaptive system that allows for optimal movement (Vereijken, van Emmerik, Whiting, & Newell, 1992). Segment couplings that begin as more in-phase in the learning stages gradually shift through practice to more out-of-phase to effectively utilise external forces and increase efficiency (Temprado, et al., 1997). The findings of the present study suggest that a consistent incorporation of a diverse collection of skating drills may help players strengthen the ability to more effectively alter their coordination and achieve efficient modes of coordination faster. The use of varied skating drill contexts may assist skaters in establishing more overall adaptive coordination and completion of these drills regularly may reinforce developed coordination patterns. For example, drills should incorporate varying combinations of speed, directionality, and external stimuli (obstacles, other players, etc.) to encourage the development of optimal coordination in a wide range of skating conditions. These proposed drills and their impact on inter-segment coordination are speculative and should be examined in experimental studies.

Limitations

There are several limitations of the present study. The sample size was small, and generalisability is limited to male hockey players with similar levels of experience. Participants used equipment that was provided for them, including a standard skate to control for potential effect of skate design, with a relatively brief amount of time to acclimate to the equipment. This may have affected their comfort level, and generalisability of the findings of this study are limited to this skate model. Players did not skate with full equipment (shoulder pads, hockey pants, etc.) which could potentially influence their segmental coordination and overall performance. Additionally, motion of the trunk and upper extremities, which would have provided additional information, were not captured. The capture area was too small to obtain information on both limbs and thus side to side differences could not be compared. Movement variability could also not be examined because additional trials would have been required.

Conclusion

In conclusion, differences exist in lower extremity inter-segment coordination between high- and low- calibre ice hockey players during full forward stride skating. High-calibre players demonstrate more out-of-phase coordination. This may allow them to more easily adjust to optimal modes of coordination throughout skating strides. Implementation of a diverse selection of skating exercises regularly may encourage the development of adaptive, more optimal coordination. Future studies should examine potential skating interventions and determine the extent to which a skating intervention will improve forward full stride skating coordination. Future studies should also examine movement variability during skating as it may provide deeper insight into optimal skating coordination.

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Table 1. Means (standard deviation) for group demographics and speed.

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)	6.01 (0.37)	5.51 (0.61)	0.064
Peak Speed (m/s)	7.39 (0.49)	6.71 (0.72)	0.043

*p value from independent t-test

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

Segment pair	*PC*	Non-Speed Model Regression Coefficients	Speed Model Regression Coefficients		
		Group*	Speed	Group	Interaction**
Shank-*sagittal* vs. Thigh-*sagittal*	1	104.57 (41.17, 167.97)	73.12 (-20.30, 125.93)	66.51 (9.05, 123.98)	N/A
	2	12.17 (-21.62, 45.96)	-38.10 (-69.34, -6.86)	31.33 (-3.04, 65.71)	N/A
	3	10.09 (-15.09, 35.28)	21.46 (-2.33, 45.26)	-0.28 (-26.17, 25.61)	N/A
Shank-*sagittal* vs. Thigh-*frontal*	1	104.90 (0.93, 208.88)	117.10 (25.18, 209.01)	46.15 (-52.83, 145.13)	N/A
	2	-34.10 (-110.13, 41.91)	67.82 (-6.24, 141.89)	-67.45 (-148.05, 13.13)	-196.26 (-313.63, -78.88)
	3	57.48 (-0.96, 115.94)	31.60 (-26.58, 89.79)	41.64 (-23.01, 106.29)	N/A
Foot-*sagittal* vs. Shank-*sagittal*	1	36.10 (-3.92, 76.13)	-16.39 (-56.57, 23.77)	44.40 (-1.12, 89.93)	N/A
	2	13.33 (-11.52, 38.20)	29.67 (9.23, 50.12)	-1.66 (-24.38, 21.05)	N/A
	3	-25.12 (-45.07, -5.17)	-12.57 (-31.97, 6.82)	-18.55 (-10.08, 2.96)	N/A

* Low-calibre participants were coded 0 and high-calibre participants were coded 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. Principal component (PC) descriptions and explained variance.

Variable	*PC*	Description	Higher *PC-scores*	Variance (%)
Shank-*sagittal* vs. Thigh-*sagittal*	1	Overall amplitude and shape	Higher CRP throughout glide and push-off	71.4
	2	Phase shift in timing	Delay in CRP decrease during push-off/early recovery	14.2
	3	Difference operator	Greater change in CRP during early glide	9.0
Shank-*sagittal* vs. Thigh-*frontal*	1	Overall amplitude and shape	Higher CRP throughout stride	54.5
	2	Difference operator	Greater change in CRP from glide to recovery	23.3
	3	Difference operator	Greater change in CRP from early glide to late glide/early recovery	13.3
Foot-*sagittal* vs. Shank-*sagittal*	1	Overall amplitude and shape	Higher CRP throughout stride	47.1
	2	Phase shift in timing	Earlier increase in CRP during push-off	20.9
	3	Difference operator	Greater change in CRP during glide to recovery	16.9

PC-scores: Principal component scores

CRP: Continuous Relative Phase

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Figure 1. Group means for (A) shank-*sagittal*/thigh-*sagittal*, (B) shank-*sagittal*/thigh-*frontal*, and (C) foot-*sagittal*/shank-*sagittal* 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. Figures will appear greyscale in print editions. Colour figures are available online.

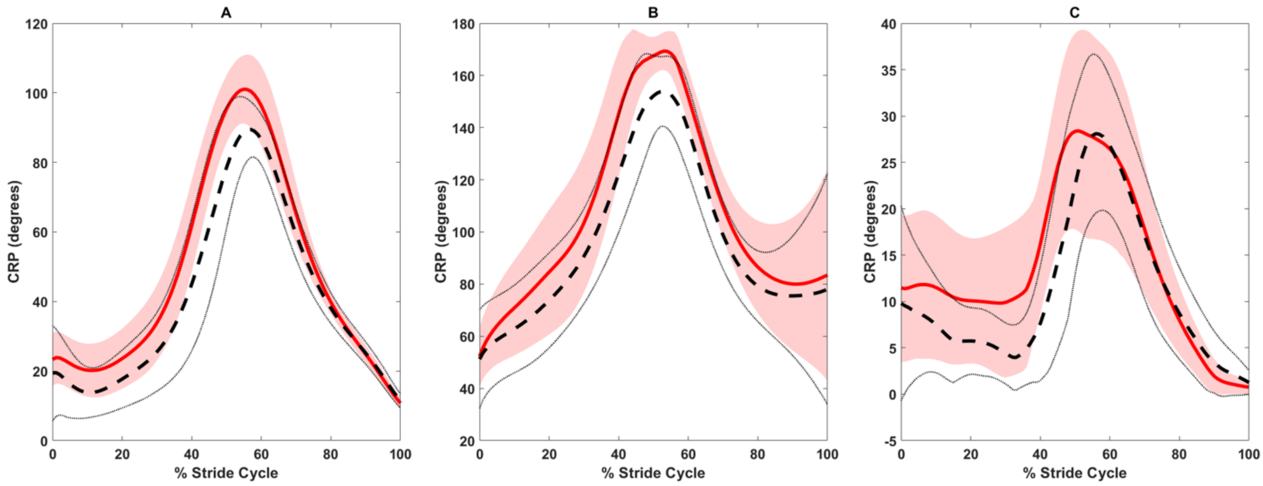

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Figure 2. Principal components (*PC*) for shank-*sagittal*/thigh-*sagittal*. (A) shank-*sagittal*/thigh-*sagittal PC1* and (B) a subset of participants that had high and low *PC1-scores* indicate that this *PC* captures higher CRP throughout glide and push-off. (C) shank-*sagittal*/thigh-*sagittal PC2* and (D) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures a delay in CRP decrease during push-off/early recovery.

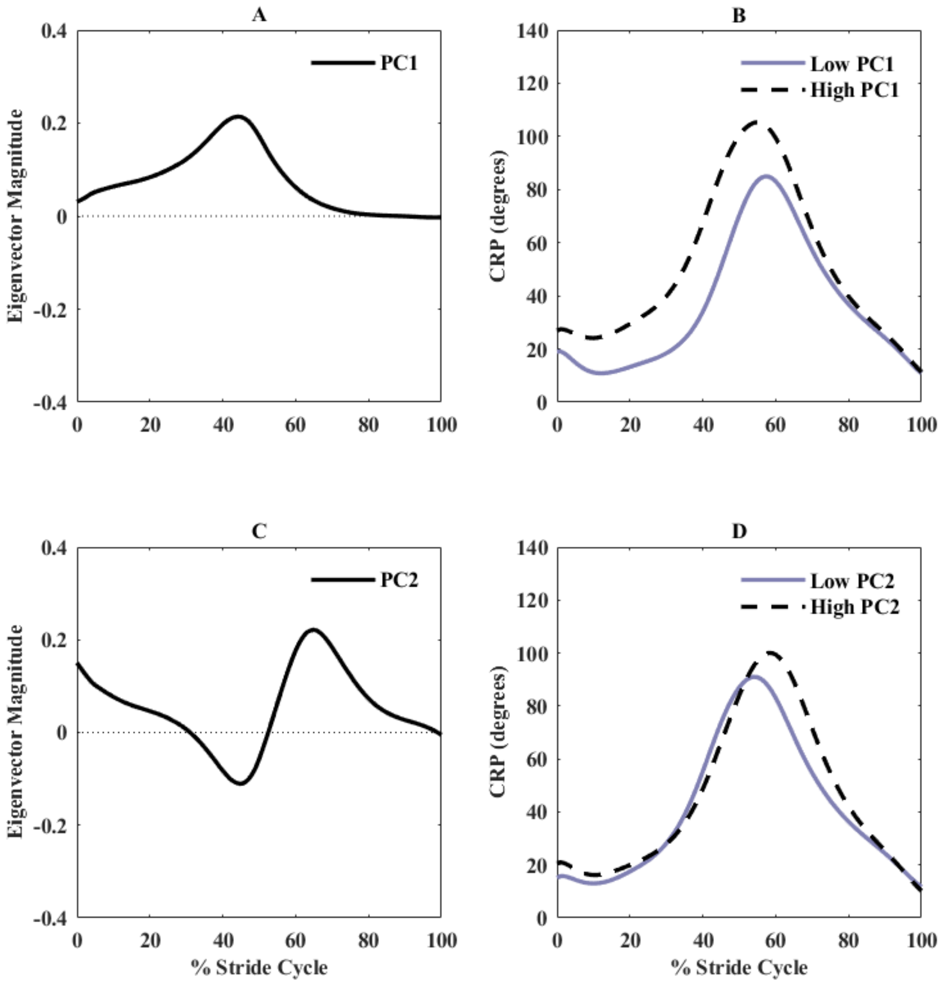


Figure 3. Principal components (*PC*) for shank-*sagittal*/thigh-*frontal.* (A) shank-*sagittal*/thigh-*frontal PC1* and (B) a subset of participants that had high and low *PC1-scores* indicate that this *PC* captures higher CRP throughout entire stride. (C) shank-*sagittal*/thigh-*frontal PC2* and (D) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures a greater change in CRP from early glide to late glide/early recovery.

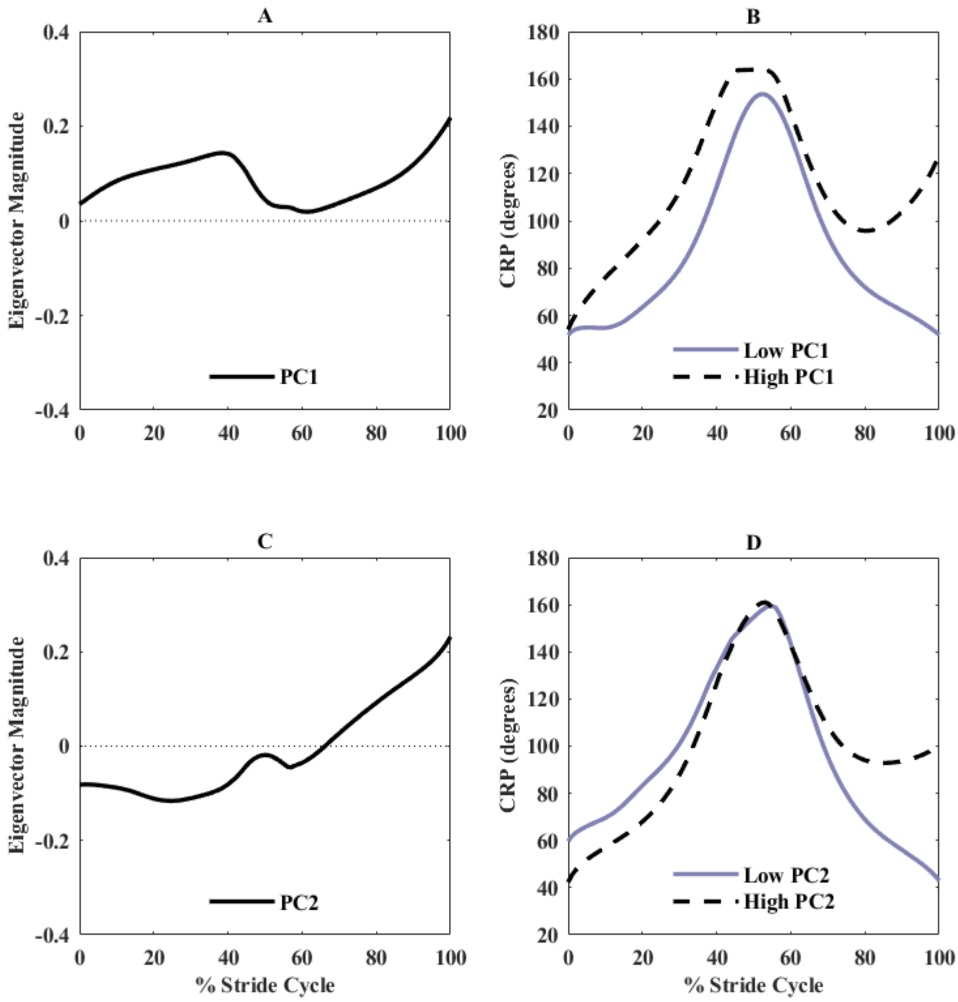


Figure 4. The relationship between average speed and shank-*sagittal*/thigh-*frontal PC2-scores* for high- and low-calibre participants. High-calibre participants are represented by red, filled dots and low-calibre participants are represented by black, unfilled dots. The lines of best fit for the high- (red, solid) and low- (black, dashed) calibre groups are also represented. Figures will appear greyscale in print editions. Colour figures are available online.

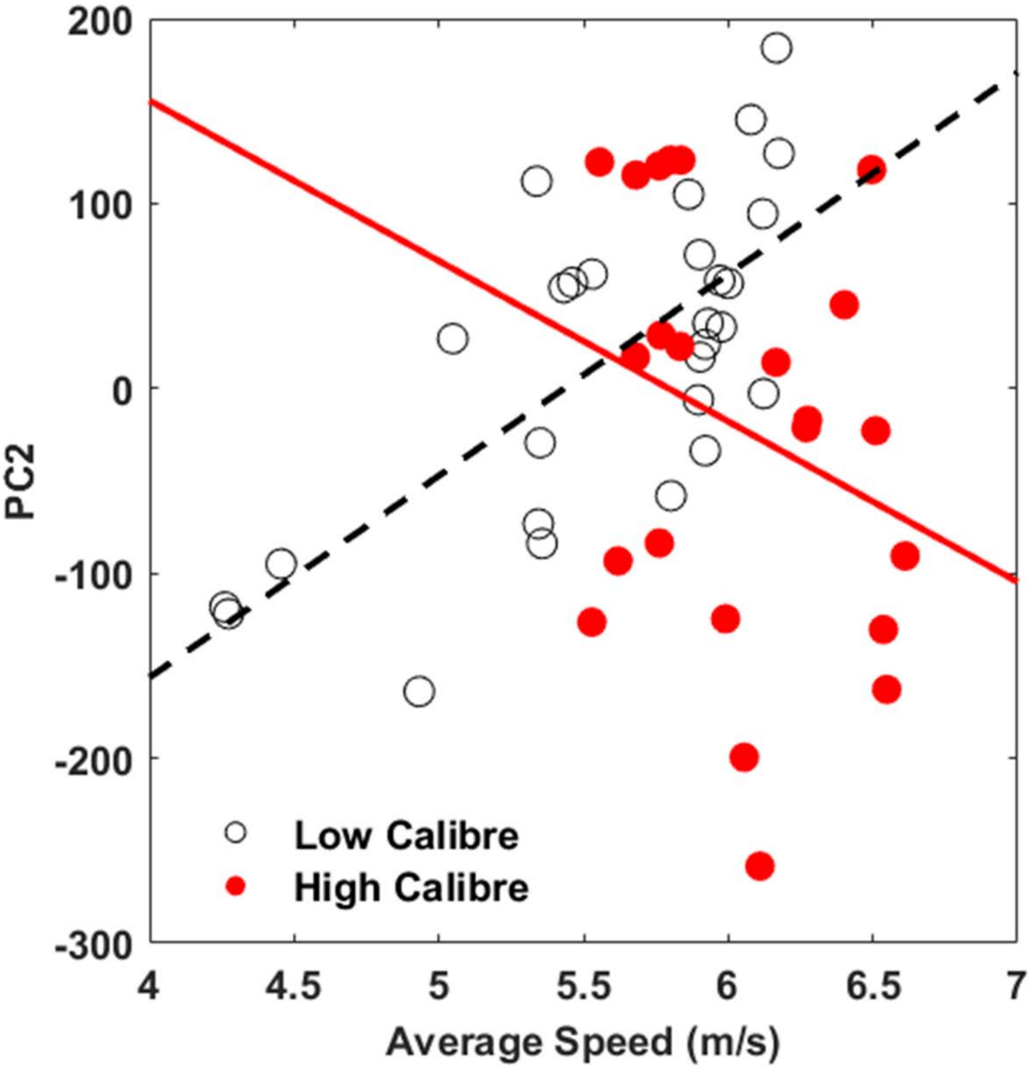
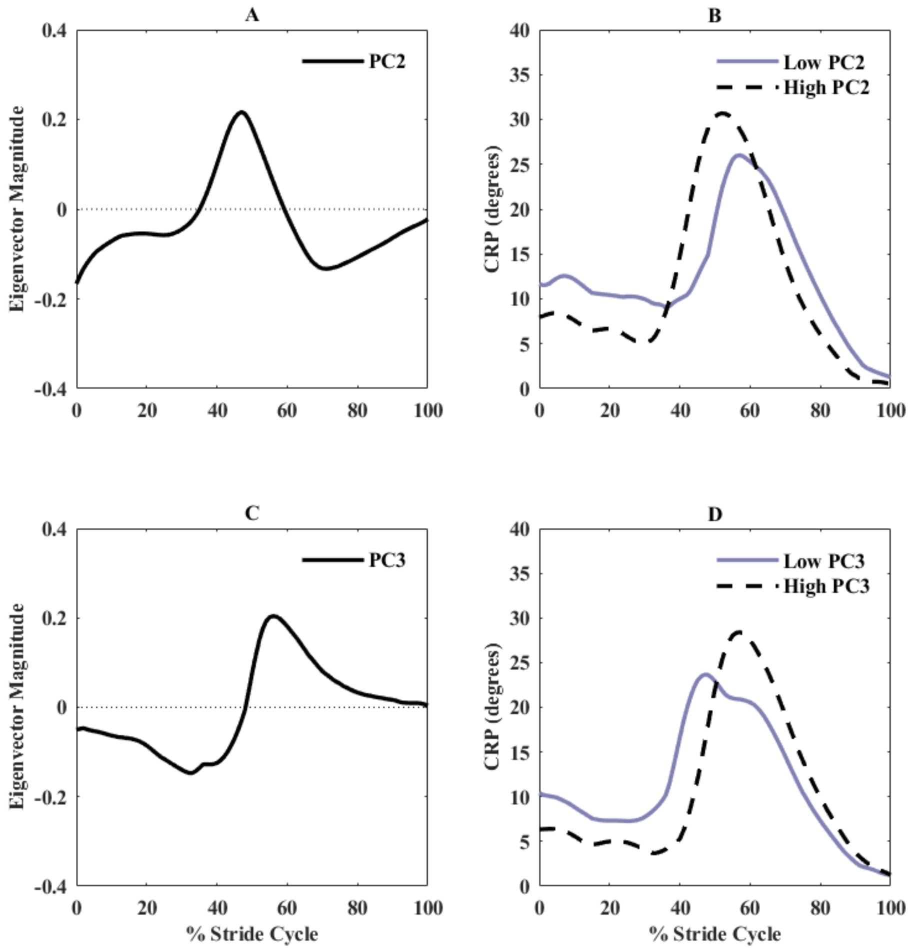


Figure 5. Principal components (*PC*) for foot-*sagittal/*shank-*sagittal.* (A) foot-*sagittal/*shank-*sagittal PC2* and (B) a subset of participants that had high and low *PC2-scores* indicate that this *PC* captures a time delay in the increase in CRP during push-off/early recovery. (C) foot-*sagittal/*shank-*sagittal PC3* and (D) a subset of participants that had high and low *PC3-scores* indicate that this *PC* captures a change in CRP between early/mid-glide and late-glide/early recovery.



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