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Principal component analysis can be used to discriminate between elite and sub-elite kicking performance

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Abstract

Contemporary descriptions of motor control suggest that variability in movement can be indicative of skilled or unskilled performance. Here we used principal component analysis (PCA) to study the kicking performance of elite and sub-elite soldiers who were highly familiar with the skill, in order to compare the variability in the first and second principal components. The subjects kicked a force plate under a range of loaded conditions, and their movement was recorded using optical motion capture. The first principal component explained > 92% of the variability across all kinematic variables when analysed separately for each condition and both groups and explained more of the variation in the movement of the elite group. There was more variation in the loading coefficient of the first principal component for the sub-elite group. In contrast, for the second principal component there was more variation in the loading coefficient for the elite group, and the relative magnitude of the variation was greater than for the first principal component for both groups. These results suggest that the first principal component represented the most fundamental movement pattern and there was less variation in this mode for the elite group. In addition, more of the variability was explained by hip than knee angle entered when both variables were entered into the same PCA which suggests that the movement is driven by the hip.

Introduction

Differences in movement variability are often proposed to typify the level of movement skill (Fleisig et al., 2009; Schorer et al., 2007). However, the nature of differences and how they equate to skill level has been the subject of considerable discussion within the literature (Daffertshofer et al., 2004; Richter et al., 2014). The naïve view is that less-skilled performers exhibit greater variation in performance and that as skill increases movement variability decreases (Stergiou & Decker, 2011). Certainly, when a person is learning a new skill there can be large differences from repetition to repetition (Wilson et al., 2008). However, this conception of skilled performance is contrary to the work of Nicolai Bernstein who showed that there was considerable joint angle variability in the hammer blows of blacksmiths (his model of skilled performance) even though the impact of the hammer itself (the actual outcome of the movement) showed less variation (Bernstein, 1967). This has led to the suggestion that increasing skill is associated with an increase in the variability of the movement strategy employed (e.g. the joint angles) while the movement outcome itself remains stable, which in turn allows a person to adapt to subtle changes in the performance environment (Betzler et al., 2012; Bradshaw et al., 2007; Seifert et al., 2011). For instance, the addition of external load (e.g. wearing a ballistic vest, backpack, or carrying a rifle) might require small but substantial changes in an elementary movement pattern like a front kick (Vagner, Cleather, et al., 2020).

If we consider human movement to be the product of a self-organizing dynamic system with the ability for learning transfer (Seidler, 2010), we can propose that fundamental movement patterns are an emergent property of the system – they are attractor states (Newell et al., 2003). Practice increases the strength of the attractor state such that variability in the pattern is reduced (Schöner et al., 1992), and also makes the pattern more likely to emerge under a wider range of different initial conditions (or constraints). However, at the same time, there can be variability in less fundamental aspects of the movement (Scholz et al., 2000; Scholz & Schöner, 1999). For instance, vertical jumping is characterized by a proximal to distal extension of the lower limb (attractor state) but there can be considerable variation in the specific contributions from the ankle, knee, and hip and their relative timings (Cleather et al., 2013). Another example of proximo-distal coupling is front kicking (S∅ rensen et al., 1996), where the proximal segments first accelerate while the distal segments lag behind, and then the proximal segments decelerate while the distal segments accelerate. Thus, the ultimate velocity of the distal segment depends on the velocity of the proximal segment and the interactions of more distal segments (Lust et al., 2009).

Recent work has demonstrated that principal component analysis (PCA) can be used to identify fundamental patterns that describe a large proportion of the variability seen in vertical jumping (Cleather & Cushion, 2019; Cushion et al., 2019, 2020). We have recently shown that there are kinetic and kinematic differences in the front kicking performances of elite and sub-elite soldiers when constrained by different types of personal protective equipment (PPE) (Vagner, Cleather, et al., 2020). In particular, we showed that elite soldiers have a shorter kick duration and a higher foot velocity. The purpose of this study was therefore to compare the same two groups using PCA to find the fundamental movement patterns. We hypothesised that the elite group would show less variability in the first principal component (which represents the most fundamental movement strategy) but that variation in the lower order principal components would be more similar.

Materials and Methods

In this cross-sectional study, 24 subjects performed sets of six kicks under five randomized loading conditions: barefoot (NL); military boots of 2 kg and a 3 kg rifle (WL1); military boots, rifle and a 10 kg ballistic vest (WL2); military boots, rifle, ballistic vest and a 15 kg backpack (WL3); and military boots, rifle, a ballistic vest, and a 30 kg backpack (WL4). All subjects attended two familiarisation sessions prior to the actual testing session. During the familiarisation session, the height of the force plate and the distance of the subject from the force plate was measured to ensure a standardized and optimal kicking position relative to the height of each subject. Subjects performed a front kick beginning from a forward-facing posture, with the aim to make contact at a height equivalent to their abdomen (Kuragano & Yokokura, 2012; Vagner, Malecek, et al., 2020). The average distance from the toe of the front foot to the force place was set to 0.9 m. After familiarisation sessions of the kicks, each subject could individually adjust this distance within ± 0.1 m. The set individual distance was recorded on the ground, and the subject performed all kicks from this distance. Prior to testing, each subject performed a 10-minute dynamic warm-up which included a set of 5 kicks into the force plate. Thirty seconds of rest was taken after each individual kick and 3 minutes of rest was taken between each set. The order of the kicking conditions was randomized and subjects were asked to perform each kick with maximal intent aiming for both the greatest velocity of movement and the maximum contact force.

Subjects

Two groups differing in kicking performance level participated in this study. The elite group included 12 close combat instructors from special military units (31.8 ± 7.8 years, 86.9 ± 4.4 kg, 179.8 ± 5.4 cm) and the sub-elite group consisted of 12 regular military forces unit members (22.6 ± 2 years, 81.1 ± 6.1 kg. 182.4 ± 6.3 cm). All participants participated in periodic front kick training using various types of PPE. Subjects provided informed written consent and the study was approved by the institutional ethics committee of the Charles University, Faculty of Physical Education (No. 50/2018. 2 February 2018) in accordance with the ethical standards of the Declaration of Helsinki.

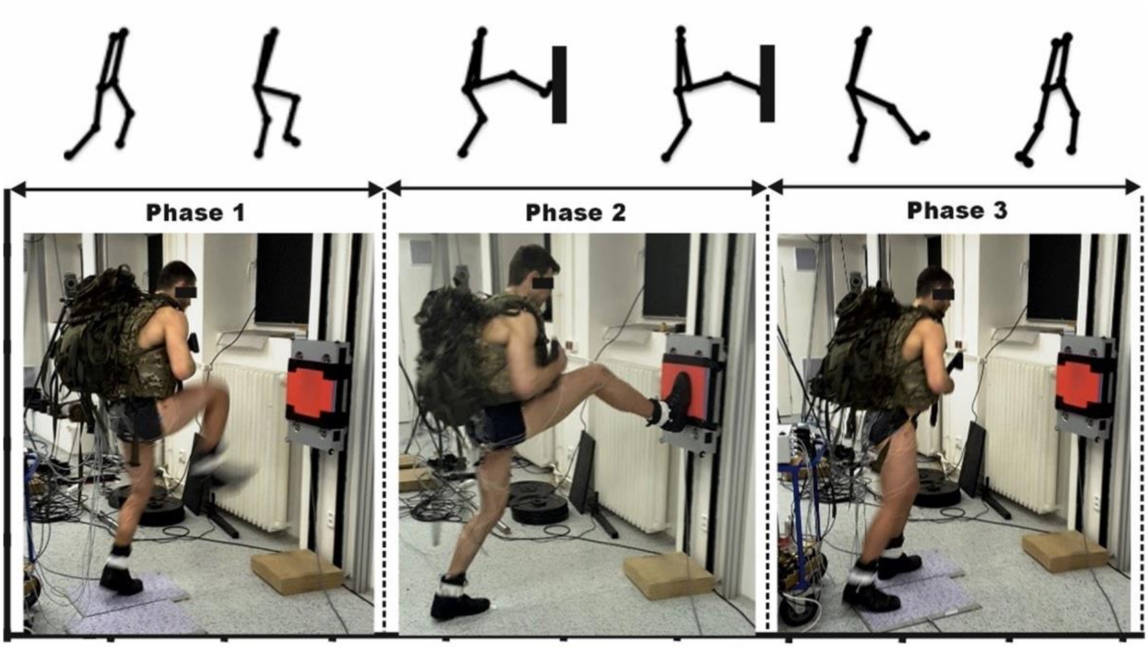
Instrumentation

Kinematic data describing each kick was collected using a 3-dimensional optical motion tracking system (6 camera Qualysis system, Qualisys AB, Göteborg, Sweden, Qualisys Track Manager 2.10) to capture the position of retro-reflective markers placed on the shoulder (acromion), hip (greater trochanter), knee (lateral epicondyle) and ankle (lateral malleolus) of the dominant (kicking) side of the subject. The contact force expressed during each kick was measured using a vertically mounted 3-axis force plate (Kistler 9281, Winterthur, Switzerland) that was synchronized with the optical motion capture system. The motion capture data were collected at 200 Hz whereas the force plate data was collected at either 500, 1000 or 5000 Hz and down-sampled to 200 Hz for analysis.

Data Analysis

Only trials for which there was a complete set of marker positions were included in the analysis Table 1). Firstly, the marker data was filtered in MATLAB® (R2020a; The Mathworks Inc., 1 Apple Hill Drive, Natick, MA 01760, USA) using a 5th order, dual low pass Butterworth filter with a cut-off frequency of 6 Hz. Next, the marker positions were used to define a simple rigid body model of each subject. The torso segment was defined to be the line connecting the shoulder and hip markers, the femur segment defined by the hip and knee markers and the tibia segment by the knee and ankle markers. The hip angle was calculated by finding the angle between the torso and femur segments, and the knee angle by the angle between the femur and tibia segments. Each kick was divided into three phases as follows (Figure 1). Firstly, pre-contact was defined as the period from foot off the ground until initial contact with the force plate. Secondly, contact was defined as the period in which the foot was in contact with the force plate. Finally, post-contact was defined as the period from when the foot left the force plate until it returned to the floor. The individual phases of each kick were time normalized separately to the average duration of the relevant phase across all kicks (pre-contact: 0.326s; contact: 0.165s; post-contact: 0.529s). The data displayed in the figures is thus normalised to a time period of 1.02s which is the sum of the three phases.

Figure 1. The front kick with full personal protective equipment illustrating the different kicking phases. Phase 1 = pre-contact, Phase 2 = contact, Phase 3 = post-contact.



For each kick, we interpolated the hip and knee angles and the contact force to produce time-series with regular intervals of 0.01s using a cubic spline within MATLAB®. For those conditions where we had more than one kick, we used the composite curve that was created by taking the average value across trials at each time point. For a limited number of subjects and conditions we did not have complete data describing a single kick (details can be seen in Table 1 of the results).

Table 1. Mean (± standard deviation) number of trials analysed per subject for each group and condition.

	NL	WL1	WL2	WL3	WL4
Elite	1.9±1.8	3.9±1.4	2.4±2.1	3.6±2.0	3.4±2.1
Sub-Elite	2.7±1.1	3.8±2.7	4.8±1.9	4.8±1.3	4.8±1.6

Legend: NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

In this study, we employed PCA in MATLAB® to compare the hip and knee angles and contact forces exhibited by the two groups. PCA is a data reduction technique that can be used to reduce the dimensionality of data and that has been used previously in biomechanics to compare time-normalized waveforms (Borzelli et al., 1999; Cleather & Cushion, 2019; Cushion et al., 2020; Deluzio & Astephen, 2007). We have previously provided a detailed description of our specific analysis approach (Cushion et al., 2019), and so only a brief description is given here. We performed a separate PCA for each variable (hip angle, knee angle or contact force), group (elite or sub-elite) and condition (NL, WL1, WL2, WL3, WL4 or all conditions) and so we ran 30 separate PCAs (3 variables × 2 groups × 5 conditions). In this study, for each PCA, each individual trial is treated as a separate dimension. Each trial consists of 103 data points and so if we have p trials (which comprise all of the trials for all of the subjects for that specific combination of variable, group and condition) our raw data can be organised in a $103 \times p$ matrix which is the input to the PCA. This analysis therefore captures both within and between individual variability for a particular variable. In addition, we performed additional PCAs where both hip and knee angles were entered into the same analysis for each group and condition and for all conditions together. This consisted of 12 separate PCAs (2 groups × 6 conditions) and captures within and between individual variability as well as joint variability). In this case, the input data was a $103 \times 2p$ matrix. Finally, we also performed PCA analyses at the individual level – i.e. for each subject we performed a separate PCA that included all of the conditions for each of the three variables separately (72 separate PCAs i.e. 24 subjects × 3 variables) and for the hip and knee angles combined (24 separate PCAs – one for each subject). If q is the number of trials for a particular subject across all conditions then the input to the PCA for the former analysis was a $103 \times q$ matrix and for the latter a $103 \times 2q$ matrix. The former analysis captured within individual variability both within and between conditions whereas the latter included this variability and the between joint variability.

The advantage of this methodology is that the resulting principal components (PCs) describe the modes of variability in the original data. In this study, we rely on three specific outputs of the PCA. Firstly, the variability described by the first two PCs is reported. Secondly, the PC score indicates how the value of the PC changes over time (note the scores are representations of the original data transformed into the coordinate space defined by the new PCs). Thirdly, loading coefficients are calculated for each time-series entered into the analysis. The loading coefficients represent the weighting of each PC score within the raw data for that time-series. That is, each raw time-series can be recovered by calculating the sum of the weighted PC scores. In the figures in this study, we present the PC scores multiplied by the mean of the loading coefficient, in order to visualise the contribution of the PC to the raw score.

Statistical Analysis

For the individual level analysis, PCs were found for each individual such that the mean variability for each PC (for each variable across all conditions) could be calculated. We performed a multivariate ANOVA with Bonferroni adjusted poc hoc tests to test for differences between elite and sub-elite groups with an alpha level of 0.05. This analysis was carried out in IBM SPSS Statistics version 28 (IBM, Armonk, NY). We also calculated Cohen's *d* in order to quantify the effect size for this comparison.

Results

For all conditions and variables, PC1 of the elite subjects described more of the within and between individual variability than PC1 of the sub-elite subjects (Table 2). The same was true for the sum of PC1 and PC2, although the difference between elite and sub-elite subjects was smaller than for PC1 alone. The within and between individual variability described by PC1 ranged from 99.0% for the hip angle of elite subjects during NL, to 88.2% for the contact force of sub-elite subjects during WL3.

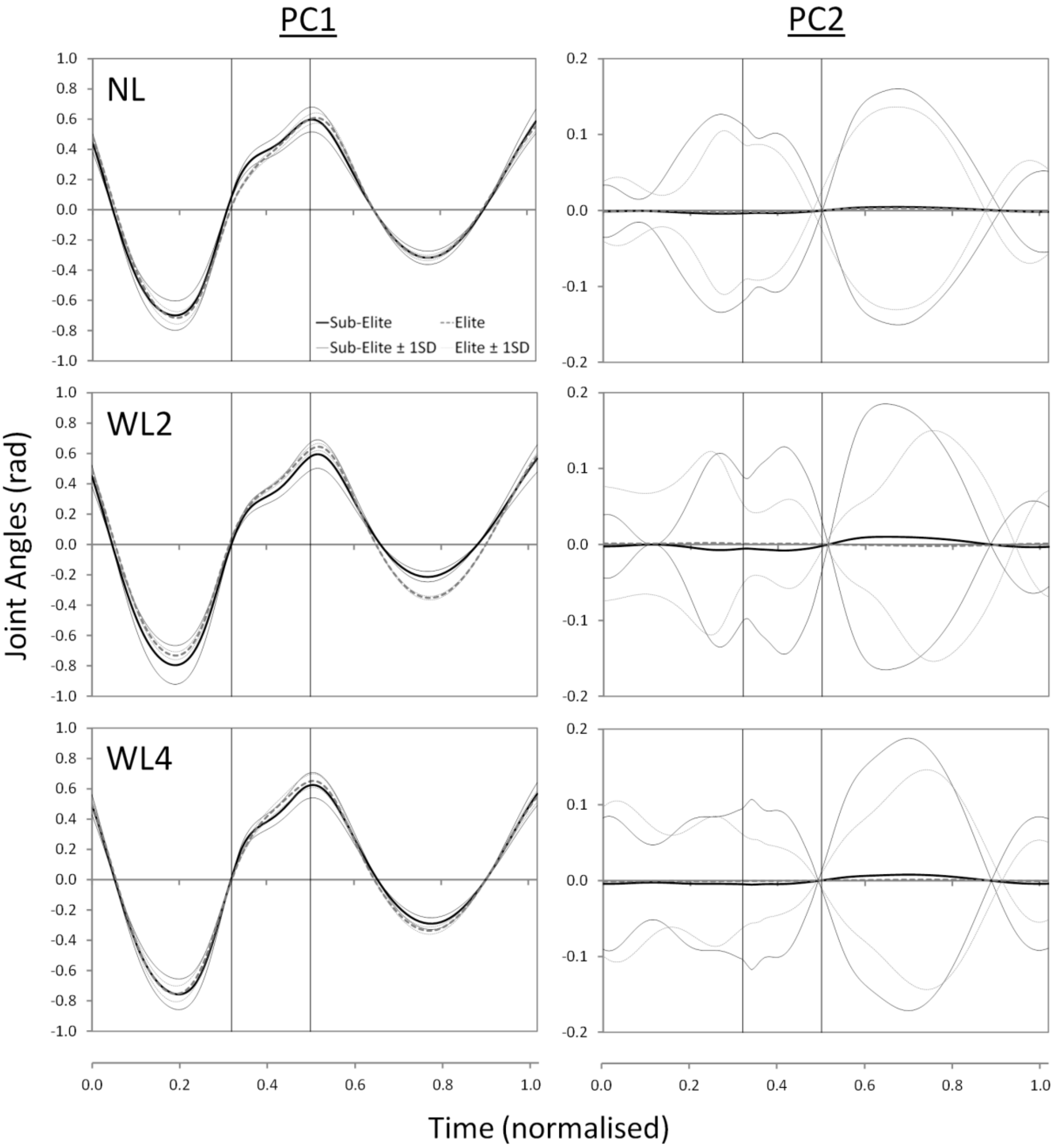
Table 2. Within and between individual variability explained by principal components (PCs) 1 and 2 for knee and hip angle and contact force during kicking by elite and sub-elite subjects across a range of conditions.

		n	% Variability Explained By:			Mean Loading Coefficient	
			PC1	PC2	Sum	PC1	PC2
Knee Angle							
NL	Elite	8	95.2	3.3	98.5	0.35 ± 0.02	-0.01 ± 0.38
	Sub-Elite	12	93.6	4.8	98.4	0.29 ± 0.04	-0.01 ± 0.30
WL1	Elite	12	94.4	3.4	97.8	0.29 ± 0.02	-0.01 ± 0.30
	Sub-Elite	10	92.2	4.4	96.6	0.31 ± 0.05	0.01 ± 0.33
WL2	Elite	8	94.9	3.5	98.5	0.35 ± 0.01	-0.01 ± 0.38
	Sub-Elite	12	92.4	5.2	97.6	0.29 ± 0.05	-0.02 ± 0.30
WL3	Elite	12	94.7	3.0	97.7	0.29 ± 0.02	0.00 ± 0.30
	Sub-Elite	12	93.7	3.9	97.6	0.29 ± 0.04	-0.01 ± 0.30
WL4	Elite	10	94.7	3.2	98.0	0.32 ± 0.02	0.00 ± 0.33
	Sub-Elite	12	92.7	5.2	97.9	0.29 ± 0.04	-0.01 ± 0.30
Hip Angle							
NL	Elite	8	99.0	0.5	99.5	0.35 ± 0.02	-0.01 ± 0.38
	Sub-Elite	12	98.3	1.1	99.4	0.29 ± 0.02	-0.01 ± 0.30
WL1	Elite	12	98.9	0.6	99.6	0.29 ± 0.01	-0.00 ± 0.30
	Sub-Elite	10	95.9	2.6	98.4	0.32 ± 0.02	0.01 ± 0.33
WL2	Elite	8	98.9	0.7	99.7	0.35 ± 0.02	0.01 ± 0.38
	Sub-Elite	12	97.4	1.6	99.0	0.29 ± 0.02	0.01 ± 0.30
WL3	Elite	12	98.8	0.6	99.4	0.29 ± 0.01	0.00 ± 0.30
	Sub-Elite	12	97.9	1.4	99.3	0.29 ± 0.03	0.01 ± 0.30
WL4	Elite	10	98.8	0.7	99.4	0.32 ± 0.02	-0.01 ± 0.33
	Sub-Elite	12	98.8	0.6	99.4	0.29 ± 0.03	-0.00 ± 0.30
Contact Force							
NL	Elite	8	95.9	3.0	98.9	0.35 ± 0.07	-0.05 ± 0.38
	Sub-Elite	12	91.9	4.2	96.1	0.28 ± 0.07	0.05 ± 0.30
WL1	Elite	12	96.6	2.2	98.8	0.29 ± 0.05	-0.03 ± 0.30
	Sub-Elite	10	95.1	2.8	97.9	0.31 ± 0.09	0.07 ± 0.32
WL2	Elite	8	96.3	3.0	99.3	0.35 ± 0.06	-0.03 ± 0.38
	Sub-Elite	12	91.8	5.0	96.7	0.28 ± 0.08	0.07 ± 0.29
WL3	Elite	12	96.1	2.3	98.4	0.28 ± 0.06	-0.02 ± 0.30
	Sub-Elite	12	88.2	7.8	95.9	0.28 ± 0.07	0.06 ± 0.30
WL4	Elite	10	96.8	1.6	98.4	0.31 ± 0.06	-0.03 ± 0.33
	Sub-Elite	12	91.1	7.0	98.2	0.28 ± 0.07	0.05 ± 0.30

Legend: The mean loading coefficient is expressed with its standard deviation. NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

There was a marked similarity between elite and sub-elite subjects in terms of the PC1 scores multiplied by the mean loading coefficient (Figure 2). For NL and WL4, the interval of the PC1 score for the elite subjects defined by the mean ± 1 standard deviation fell within the equivalent interval for the sub-elite subjects across all time points. The same was true for WL2 prior to and during contact, however, after contact the elite subjects exhibited more knee flexion for WL2. A full set of PC1 and PC2 scores for both knee and hip angles for all conditions are presented in the Supplementary Web Content (Supplementary Figures 1 and 2).

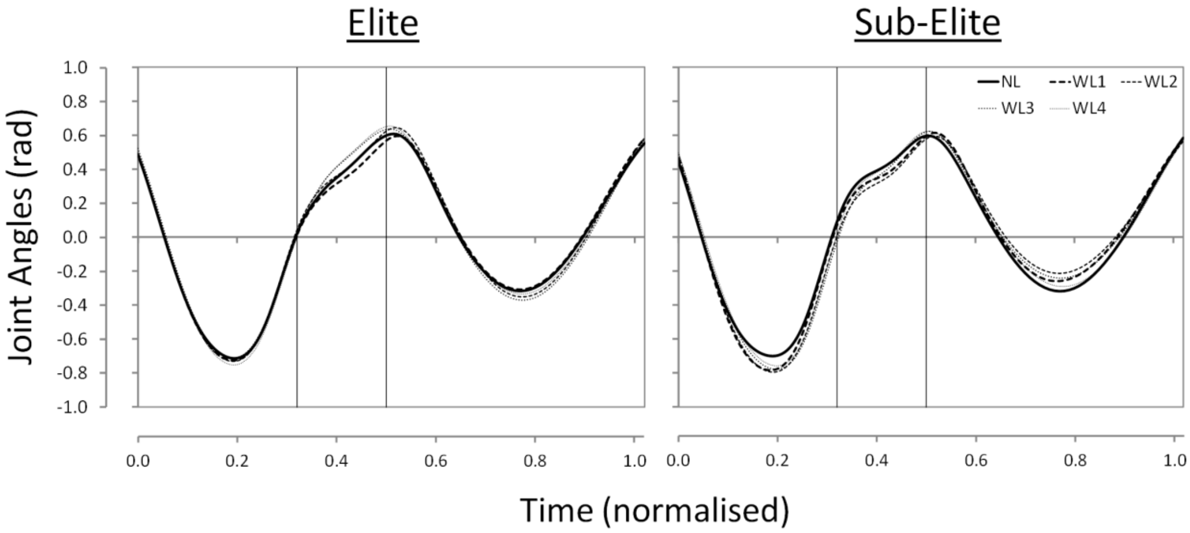
Figure 2. Principal component (PC) scores of knee angle multiplied by mean loading coefficients for elite and sub-elite subjects during kicking for selected conditions.



Legend: NL= no load barefoot kick; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg. Thinner lines indicate PC scores multiplied by mean loading coefficients ± 1 standard deviation. Vertical lines at t = 0.32 and t = 0.5 indicate the contact period during the kick. Joint angles are centred around the mean joint angle and more positive values are indicative of joint extension.

When comparing across conditions, for the elite subjects, there was very little difference in the PC1 scores multiplied by the mean loading coefficients prior to contact, whereas the sub-elite subjects exhibited greater knee flexion prior to contact during the weighted conditions as compared to NL (Figure 3). After contact, the elite subjects tended to exhibit greater knee flexion in the weighted conditions, whereas in contrast, the sub-elite subjects exhibited reduced knee flexion.

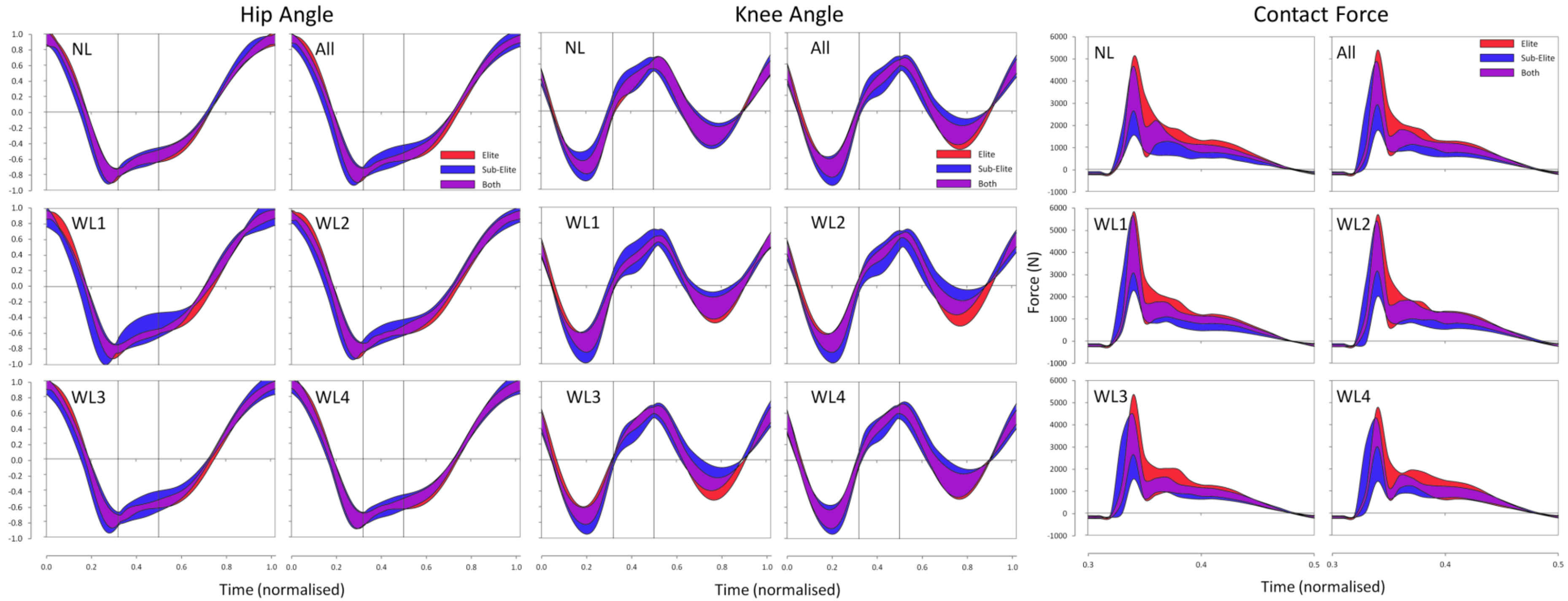
Figure 3. Principal component (PC) scores of knee angle for PC1 multiplied by mean loading coefficients for elite and sub-elite subjects during kicking across a range of conditions.



Legend: NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg. Thinner lines indicate PC scores multiplied by mean loading coefficients ± 1 standard deviation. Vertical lines at t = 0.32 and t = 0.5 indicate the contact period during the kick. Joint angles are centered around the mean joint angle and more positive values are indicative of joint extension.

Figure 4 illustrates the variation in the sum of the scores for PC1 and PC2 for knee and hip angles. For the NL condition, the variation in scores was smaller for the elite subjects and the range of scores for the elite subjects again largely fell within the range of the sub-elite subjects. However, for the weighted conditions the sum of the scores did not coincide so closely, and the elite subjects showed more knee and hip flexion post contact. For knee angle, the differences between the two groups were largest for WL2 and WL3, whereas for hip angle the difference was largest for WL1. Figure 4 also indicates that the elite subjects expressed a greater contact force during the duration of the kick and a greater rate of force development in the early part of the contact phase.

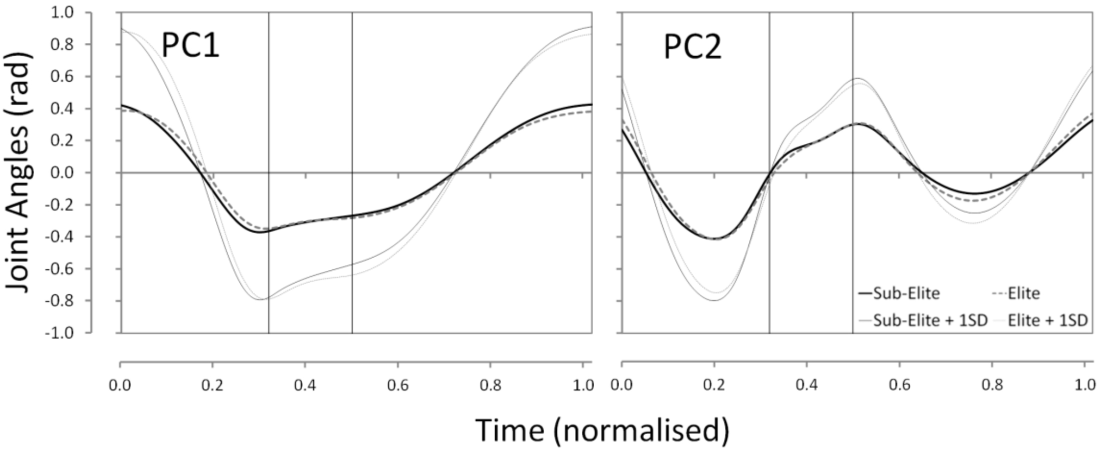
Figure 4. Sum of the principal component (PC) scores of knee angle, hip angle and contact force, for PC1 and PC2 multiplied by mean loading coefficients ± 1 standard deviation for elite and sub-elite subjects during kicking across a range of conditions.



Legend: NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg. Thinner lines indicate PC scores multiplied by mean loading coefficients ± 1 standard deviation. Vertical lines at t = 0.32 and t = 0.5 indicate the contact period during the kick. Joint angles are centered around the mean joint angle and more positive values are indicative of joint extension.

When both hip and knee angles were entered into the same PCA, PC1 was clearly hip-like and PC2 was knee-like (Figure 5). PC1 described a greater proportion of the within and between individual and between joint variability for the elite subjects as compared to the sub-elite subjects for all conditions (Table 3).

Figure 5. Principal component (PC) scores of hip and knee angle multiplied by mean loading coefficients for elite and sub-elite subjects during kicking across all conditions.



Legend: Thinner lines indicate PC scores multiplied by mean loading coefficients + 1 standard deviation. Vertical lines at t = 0.32 and t = 0.5 indicate the contact period during the kick. Joint angles are centred around the mean joint angle.

Table 3. Within and between individual and between joint variability in knee and hip angles explained by principal components (PCs) 1 and 2 during kicking by elite and sub-elite subjects across a range.

		n	% Variability Explained By:		
			PC1	PC2	Sum
NL	Elite	8	69.0	29.3	98.3
	Sub-Elite	12	67.7	29.7	97.4
WL1	Elite	12	69.9	28.3	98.1
	Sub-Elite	10	64.0	32.9	96.9
WL2	Elite	8	67.5	30.5	98.1
	Sub-Elite	12	64.5	32.4	96.9
WL3	Elite	12	67.8	30.2	98.0
	Sub-Elite	12	65.5	32.1	97.5
WL4	Elite	10	66.8	31.1	97.9
	Sub-Elite	12	66.2	31.2	97.4
All	Elite	50	68.2	29.8	98.0
	Sub-Elite	58	65.5	31.5	97.0

Legend: NL= no load barefoot kick, WL1 = 5kg – 2 kg military boots and 3 kg rifle; WL2 = 15kg – 2 kg military boots, 3 kg rifle and 10kg ballistic vest; WL3 = 30kg - 2 kg military boots, 3 kg rifle, 10kg ballistic vest and 15kg back pack; WL4 = 45kg - 2 kg military boots, 3 kg rifle, 10kg ballistic vest and 30kg back pack.

The individual level analysis also demonstrated that PC1 explained a greater proportion of the mean within individual variability for the elite subjects for all variables (Table 4). These differences were statistically significant and of large effect size for hip angle (p = 0.009, d = 1.02) and contact force (p = 0.003, d = 1.13).

Table 4. Mean within individual variability explained by principal components (PCs) 1 and 2 for knee and hip angle and contact force during kicking by elite and sub-elite subjects. Principal component analysis was performed separately for each individual and variable but included all conditions. Note that for the combined knee and hip angle analysis the variability derives from both within individual and between joint sources.

		% Variability Explained By:		
		PC1	PC2	Sum
Knee Angle	Elite	98.7 ± 1.1	1.0 ± 1.0	99.8 ± 0.1
	Sub-Elite	98.2 ± 1.0	1.3 ± 0.8	99.5 ± 0.4
	ES (Cohen's *d*)	0.54	0.30	0.82*
Hip Angle	Elite	99.8 ± 0.1	0.2 ± 0.1	100.0 ± 0.0
	Sub-Elite	99.2 ± 0.6	0.6 ± 0.4	99.8 ± 0.2
	ES (Cohen's *d*)	1.02*	1.07*	0.71
Contact Force	Elite	99.1 ± 0.6	0.8 ± 0.5	99.8 ± 0.1
	Sub-Elite	96.7 ± 2.4	2.9 ± 2.3	99.6 ± 0.5
	ES (Cohen's *d*)	1.13*	1.08*	0.73
Knee and Hip Angles	Elite	68.9 ± 3.2	30.6 ± 3.1	99.5 ± 0.3
	Sub-Elite	67.0 ± 5.4	32.3 ± 5.4	99.2 ± 0.4
	ES (Cohen's *d*)	0.44	0.37	0.80

Legend: ES = effect size; * = significantly different ($p < 0.05$).

Discussion

The purpose of this study was to use PCA to analyse the differences in the movement strategies employed by elite and sub-elite subjects when performing a kicking task across a range of conditions. Overall, the variability in hip and knee angles explained by PC1 is greater for elite subjects and the dispersion of the loading coefficient for PC1 is also lower for the elite subjects (Table 2). Taken together, these observations indicate that there was much less within and between subject variation in the movement strategy employed by the elite subjects when compared to their sub-elite counterparts. As the magnitude of the difference in the within subject variability seen in the individual analysis was smaller than for the group analysis (even taking into account that the individual analysis included all conditions; Table 4) this suggests that there was less between subject variability in the elite subjects. This trend was seen despite there being much greater variability in the ages of the elite subjects. Although this main result is in agreement with the basic motor control presumption of increasing movement precision with increased skill (Stergiou & Decker, 2011), there is also evidence of an increased possibility of precise movement variations in more experienced athletes across different PPE conditions (Bernstein, 1967). The substantial differences between the elite and sub-elite subjects across conditions are discussed below.

The example in Figure 2 and Supplementary Figure 1 indicates that for the NL condition, the weighted PC1 scores for knee and hip angle for the two groups were qualitatively similar for both elite (knee 95.2%, hip 99.0%) and sub-elite subjects (knee 93.6%, hip 98.3). This indicates that there was a fundamental characteristic pattern of knee and hip angle over time that was remarkably similar between the two groups, where the groups differed in the dispersion of the PC1 scores as expressed by the standard deviation of the loading coefficients. As can be seen in Figure 2 and Supplementary Figure 1, this was much greater for the sub-elite group, indicating that although the pattern was similar at a group level, there was more inter-individual variation when it came to the relative magnitudes of knee and hip flexion and extension during the movement. In contrast, for PC2 the standard deviation of the loading coefficient for the elite group was greater and the dispersion of the PC2 scores much more similar. This finding seems to be contradictory to the presumption that elite level athletes have a large specificity of their movements resulting in functionality by movement variability (Bartlett et al., 2007; Preatoni et al., 2013), which has been shown in a golf swing (Tucker et al., 2013) or basketball shot (Wagner et al., 2012). However, it is important to note that here we are reporting the single joint variability and not the joint coupling strategy, and thus we can suggest that as skill increases the single joint pattern is more stable. We would advance the following speculative explanation for these observations. It would seem that the PC1 score represents a characteristic pattern that is exhibited within a front kick of this type, and that as skill increases there is less variation between the executors in this pattern – it becomes more stable. To use the language of dynamic systems theory, this is an attractor state. The loading coefficients simply represent a scaling factor that changes the magnitude of the curve, and thus the standard deviations of the loading coefficients don't represent any variation in the nature of the pattern apart from its relative size. Instead, for any particular trial, the principal mode of variation from the attractor state is described by the PC2 score. For the NL condition, the pattern of this variation was markedly similar between the two groups and the dispersion across individuals was of the same order of magnitude. That is, for the PC2 score, increasing skill level does not meaningfully decrease the variation.

In Figure 3, the changes in the weighted PC1 scores for the two groups are compared across conditions. In the period prior to contact, there is very little variation in the PC1 scores across conditions for the elite group, whereas the sub-elite group exhibited greater peak knee flexion in the weighted conditions. Using the language of dynamic systems theory, it appears that for the elite group prior to contact the attractor state has become strong enough that the pattern is largely invariant across conditions, whereas for the sub-elite group either a different strategy is being employed and/or there is more variation in the execution of the movement. This effect is also described in other studies, where increased load was associated with decreases in postural stability (LaGoy et al., 2020). The exception to this is for WL4 where the elite group also exhibited greater peak knee flexion prior to contact which seems indicative of a less stable performance than the other conditions. This in turn could be characterised as WL4 being sufficiently challenging that even the performance of the elite subjects was compromised. This observation is consistent with our previous analysis of the same dataset (Vagner, Cleather, et al., 2020). It is notable that when the movement begins to "break down" under these increasing demands, it does so in a similar way for both groups, and the movement of the elite subjects resembles that of their sub-elite counterparts.

In contrast to the period before contact, after contact the PC1 scores of both groups deviated from the NL pattern in the weighted conditions. For the elite group this was largely an increase in peak knee flexion, with the dispersion of the PC1 scores of similar magnitude to NL, whereas for the sub-elite group there was a decrease in peak knee flexion (Figure 2). This then seems to be indicative of a different strategy used by the elite subjects across conditions – subtly different attractor states. It seems plausible that such a difference might be a hallmark of elite level skilled behaviour. The idea that the two groups used different strategies after contact is also supported by a consideration of the PC2 scores – these are markedly different post contact. In particular, the variability in peak knee flexion represented by the PC2 scores, occurs later in the post contact phase for the elite subjects. Typically, post-contact movements are the result of previous movement mechanics, and are in practice used for technique corrections during training (Stastny et al., 2015).

Figure 4 presents the dispersion of possible values of knee and hip angles (within one standard deviation of the mean loading coefficient) of the sum of the weighted PC1 and PC2 scores. For NL, the elite group's performance largely lies centrally within the range of values seen in the sub-elite group. Across the first three weighted conditions, there is some deviation in the performance of the task between the two groups. The largest variation is seen post contact in WL2, where the elite group exhibits greater peak knee flexion which occurs later in the phase. We suggest this represents the greater skill level of the elite subjects in using a more appropriate movement strategy, as the elite group exhibited higher force magnitude with higher force gradient for all loading conditions during the contact phase (Figure 4). For WL4, there is much less deviation between the two groups, which we suggest is a result of the elite group's performance beginning to break down under the more demanding task constraints, and thus starting to approximate the less skilled performance of the sub-elite group. The same trends across weighted conditions can be seen in terms of the hip angle (Figure 4) – that is, the movement patterns for the two groups were most similar for NL and WL4.

In this study, we also entered hip and knee angles into the same PCA. The results of this analysis were that PC1 was “hip-like” and PC2 was “knee-like” (Table 3 and Figure 5). Consequently, we conclude that the hip angle explains more of the variability in kinematics than the knee angle. This can be interpreted as the movement being “driven” by the hip. This is consistent with the fact that there was more variability in knee angle than hip angle (Figure 4) – variation in knee angle is a function of variation in hip angle in addition to the knee specific variation. PC1 explained more of the variance in kinematics for the elite subjects than for the sub-elite subjects across all conditions (Table 3). This indicates that the movement of hip and knee is more closely coordinated for the elite subjects – the hip being a relatively more important driver of the movement, which is in line with previous research suggesting that hip muscle strength is probably the dominant muscular factor for determining kick performance (Moreira et al., 2020).

In this study we found that PC1 from the group analysis (Table 2) represented the most fundamental pattern of movement for each particular joint, and that more skilled subjects exhibited less dispersion of their PC1 scores. In contrast, the dispersion of the PC2 scores was more similar between the two groups of subjects, and for the elite group provided variability in the timing of peak knee flexion post contact. Finally, this study provides evidence that more skilful movements are more tightly driven by the proximal joints, in this case the hip.

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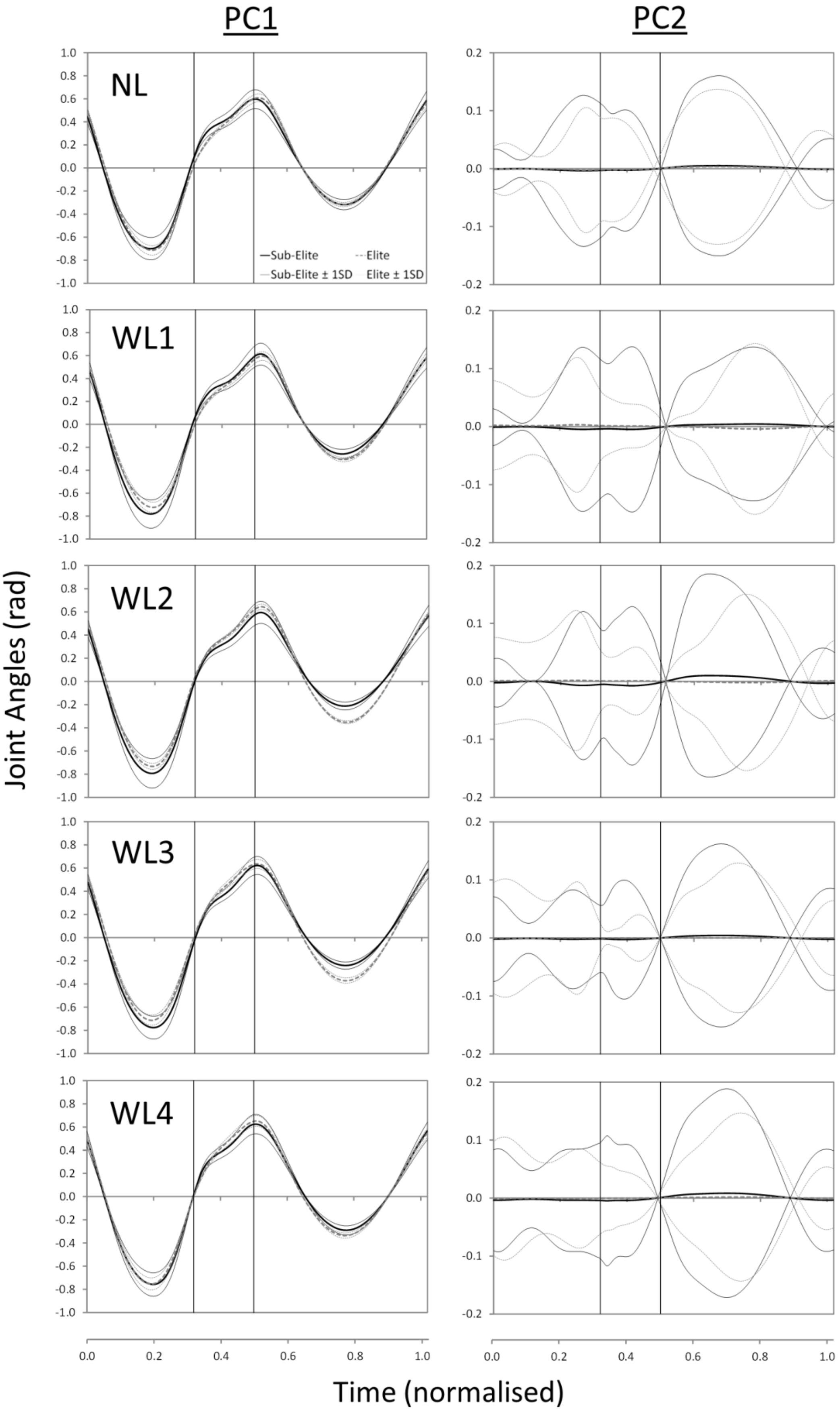
Supplementary Figure 1



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Supplementary Figure 2