

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

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16

17 **Abstract**

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

34 **Introduction**

35 Differences in movement variability are often proposed to typify the level of movement skill
36 (Fleisig et al., 2009; Schorer et al., 2007). However, the nature of differences and how they
37 equate to skill level has been the subject of considerable discussion within the literature
38 (Daffertshofer et al., 2004; Richter et al., 2014). The naïve view is that less-skilled performers
39 exhibit greater variation in performance and that as skill increases movement variability
40 decreases (Stergiou & Decker, 2011). Certainly, when a person is learning a new skill there

41 can be large differences from repetition to repetition (Wilson et al., 2008). However, this
42 conception of skilled performance is contrary to the work of Nicolai Bernstein who showed
43 that there was considerable joint angle variability in the hammer blows of blacksmiths (his
44 model of skilled performance) even though the impact of the hammer itself (the actual outcome
45 of the movement) showed less variation (Bernstein, 1967). This has led to the suggestion that
46 increasing skill is associated with an increase in the variability of the movement strategy
47 employed (e.g. the joint angles) while the movement outcome itself remains stable, which in
48 turn allows a person to adapt to subtle changes in the performance environment (Betzler et al.,
49 2012; Bradshaw et al., 2007; Seifert et al., 2011). For instance, the addition of external load
50 (e.g. wearing a ballistic vest, backpack, or carrying a rifle) might require small but substantial
51 changes in an elementary movement pattern like a front kick (Vagner, Cleather, et al., 2020).

52 If we consider human movement to be the product of a self-organizing dynamic system with
53 the ability for learning transfer (Seidler, 2010), we can propose that fundamental movement
54 patterns are an emergent property of the system – they are attractor states (Newell et al., 2003).
55 Practice increases the strength of the attractor state such that variability in the pattern is reduced
56 (Schöner et al., 1992), and also makes the pattern more likely to emerge under a wider range
57 of different initial conditions (or constraints). However, at the same time, there can be
58 variability in less fundamental aspects of the movement (Scholz et al., 2000; Scholz & Schöner,
59 1999). For instance, vertical jumping is characterized by a proximal to distal extension of the
60 lower limb (attractor state) but there can be considerable variation in the specific contributions
61 from the ankle, knee, and hip and their relative timings (Cleather et al., 2013). Another example
62 of proximo-distal coupling is front kicking (Sørensen et al., 1996), where the proximal
63 segments first accelerate while the distal segments lag behind, and then the proximal segments
64 decelerate while the distal segments accelerate. Thus, the ultimate velocity of the distal segment

65 depends on the velocity of the proximal segment and the interactions of more distal segments
66 (Lust et al., 2009).

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

78 **Materials and Methods**

79 In this cross-sectional study, 24 subjects performed sets of six kicks under five randomized
80 loading conditions: barefoot (NL); military boots of 2 kg and a 3 kg rifle (WL1); military boots,
81 rifle and a 10 kg ballistic vest (WL2); military boots, rifle, ballistic vest and a 15 kg backpack
82 (WL3); and military boots, rifle, a ballistic vest, and a 30 kg backpack (WL4). All subjects
83 attended two familiarisation sessions prior to the actual testing session. During the
84 familiarisation session, the height of the force plate and the distance of the subject from the
85 force plate was measured to ensure a standardized and optimal kicking position relative to the
86 height of each subject. Subjects performed a front kick beginning from a forward-facing
87 posture, with the aim to make contact at a height equivalent to their abdomen (Kuragano &
88 Yokokura, 2012; Vagner, Malecek, et al., 2020). The average distance from the toe of the front

89 foot to the force plate was set to 0.9 m. After familiarisation sessions of the kicks, each subject
90 could individually adjust this distance within ± 0.1 m. The set individual distance was recorded
91 on the ground, and the subject performed all kicks from this distance. Prior to testing, each
92 subject performed a 10-minute dynamic warm-up which included a set of 5 kicks into the force
93 plate. Thirty seconds of rest was taken after each individual kick and 3 minutes of rest was
94 taken between each set. The order of the kicking conditions was randomized and subjects were
95 asked to perform each kick with maximal intent aiming for both the greatest velocity of
96 movement and the maximum contact force.

97 ***Subjects***

98 Two groups differing in kicking performance level participated in this study. The elite group
99 included 12 close combat instructors from special military units (31.8 ± 7.8 years, 86.9 ± 4.4
100 kg, 179.8 ± 5.4 cm) and the sub-elite group consisted of 12 regular military forces unit members
101 (22.6 ± 2 years, 81.1 ± 6.1 kg, 182.4 ± 6.3 cm). All participants participated in periodic front
102 kick training using various types of PPE. Subjects provided informed written consent and the
103 study was approved by the institutional ethics committee of the Charles University, Faculty of
104 Physical Education (No. 50/2018, 2 February 2018) in accordance with the ethical standards
105 of the Declaration of Helsinki.

106 ***Instrumentation***

107 Kinematic data describing each kick was collected using a 3-dimensional optical motion
108 tracking system (6 camera Qualysis system, Qualisys AB, Göteborg, Sweden, Qualisys Track
109 Manager 2.10) to capture the position of retro-reflective markers placed on the shoulder
110 (acromion), hip (greater trochanter), knee (lateral epicondyle) and ankle (lateral malleolus) of
111 the dominant (kicking) side of the subject. The contact force expressed during each kick was
112 measured using a vertically mounted 3-axis force plate (Kistler 9281, Winterthur, Switzerland)

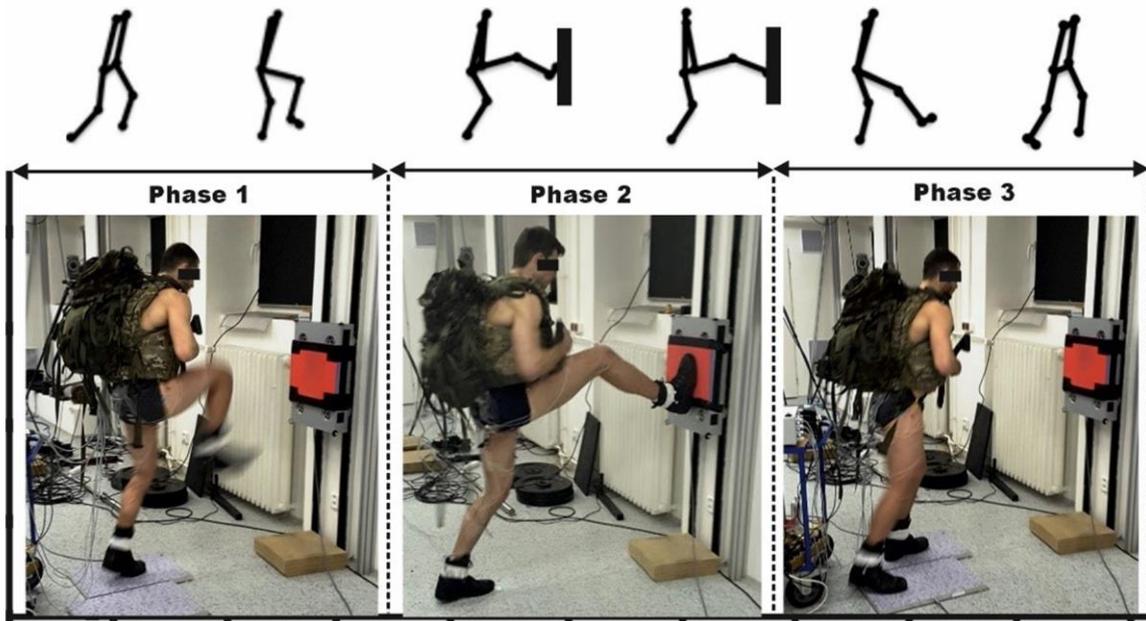
113 that was synchronized with the optical motion capture system. The motion capture data were
114 collected at 200 Hz whereas the force plate data was collected at either 500, 1000 or 5000 Hz
115 and down-sampled to 200 Hz for analysis.

116 *Data Analysis*

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

133

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



136
 137

138 For each kick, we interpolated the hip and knee angles and the contact force to produce time-
 139 series with regular intervals of 0.01s using a cubic spline within MATLAB®. For those
 140 conditions where we had more than one kick, we used the composite curve that was created by
 141 taking the average value across trials at each time point. For a limited number of subjects and
 142 conditions we did not have complete data describing a single kick (details can be seen in Table
 143 1 of the results).

144 Table 1. Mean (\pm standard deviation) number of trials analysed per subject for each group
 145 and condition.

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

146 **Legend:** NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots
 147 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
 148 pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.

149

150 In this study, we employed PCA in MATLAB® to compare the hip and knee angles and contact
151 forces exhibited by the two groups. PCA is a data reduction technique that can be used to reduce
152 the dimensionality of data and that has been used previously in biomechanics to compare time-
153 normalized waveforms (Borzelli et al., 1999; Cleather & Cushion, 2019; Cushion et al., 2020;
154 Deluzio & Astephen, 2007). We have previously provided a detailed description of our specific
155 analysis approach (Cushion et al., 2019), and so only a brief description is given here. We
156 performed a separate PCA for each variable (hip angle, knee angle or contact force), group
157 (elite or sub-elite) and condition (NL, WL1, WL2, WL3, WL4 or all conditions) and so we ran
158 30 separate PCAs (3 variables \times 2 groups \times 5 conditions). In this study, for each PCA, each
159 individual trial is treated as a separate dimension. Each trial consists of 103 data points and so
160 if we have p trials (which comprise all of the trials for all of the subjects for that specific
161 combination of variable, group and condition) our raw data can be organised in a $103 \times p$ matrix
162 which is the input to the PCA. This analysis therefore captures both within and between
163 individual variability for a particular variable. In addition, we performed additional PCAs
164 where both hip and knee angles were entered into the same analysis for each group and
165 condition and for all conditions together. This consisted of 12 separate PCAs (2 groups \times 6
166 conditions) and captures within and between individual variability as well as joint variability).
167 In this case, the input data was a $103 \times 2p$ matrix. Finally, we also performed PCA analyses at
168 the individual level – i.e. for each subject we performed a separate PCA that included all of the
169 conditions for each of the three variables separately (72 separate PCAs i.e. 24 subjects \times 3
170 variables) and for the hip and knee angles combined (24 separate PCAs – one for each subject).
171 If q is the number of trials for a particular subject across all conditions then the input to the
172 PCA for the former analysis was a $103 \times q$ matrix and for the latter a $103 \times 2q$ matrix. The
173 former analysis captured within individual variability both within and between conditions
174 whereas the latter included this variability and the between joint variability.

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

185 *Statistical Analysis*

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

192 **Results**

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

199 **Table 2.** Within and between individual variability explained by principal components (PCs)
 200 1 and 2 for knee and hip angle and contact force during kicking by elite and sub-elite subjects
 201 across a range of conditions.

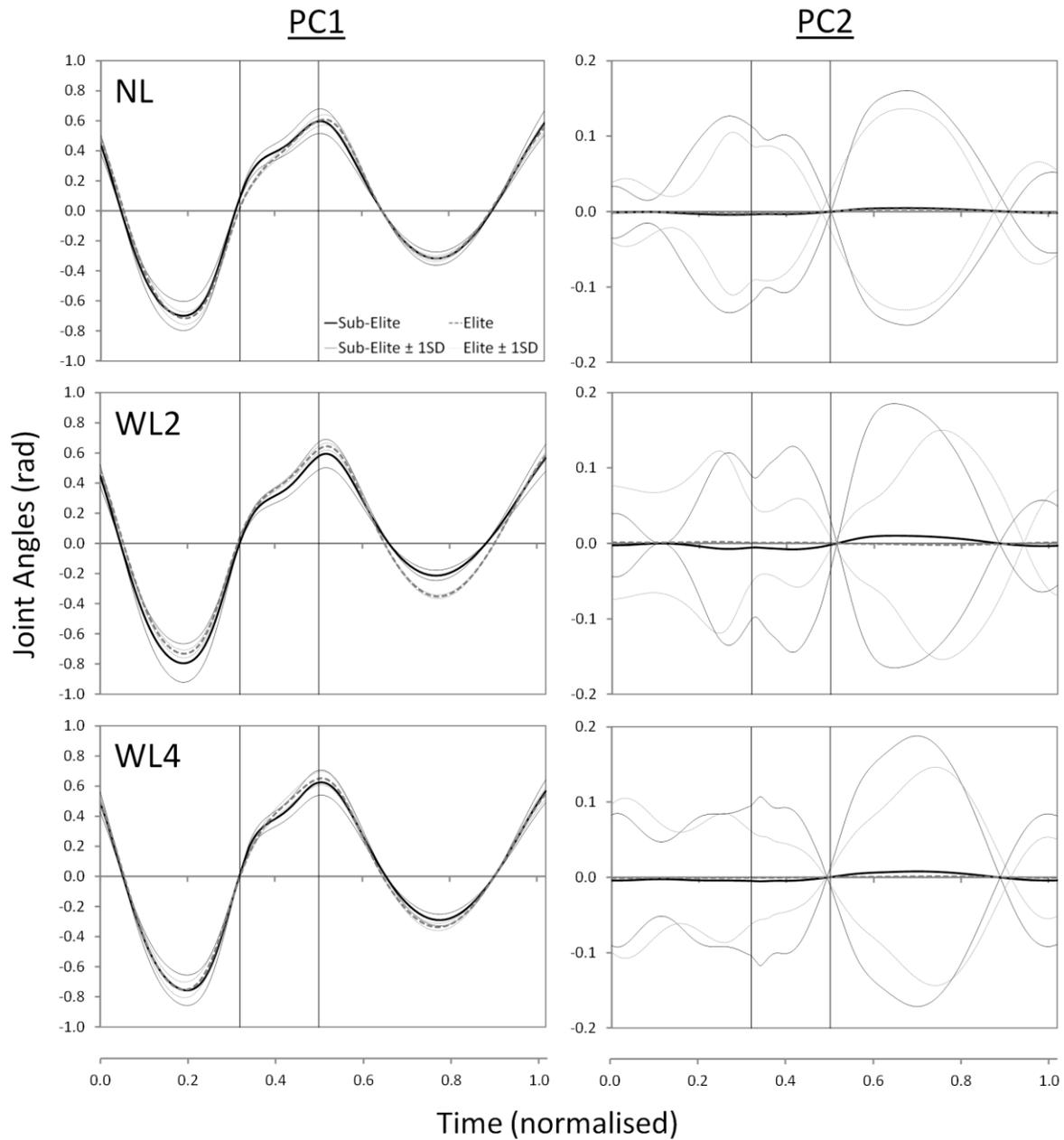
		n	% Variability Explained By:			Mean Loading Coefficient	
			PC1	PC2	Sum	PC1	PC2
Knee Angle							
NL	Elite	8	95.2	3.3	98.5	0.35 ± 0.02	-0.01 ± 0.38
	Sub-Elite	12	93.6	4.8	98.4	0.29 ± 0.04	-0.01 ± 0.30
WL1	Elite	12	94.4	3.4	97.8	0.29 ± 0.02	-0.01 ± 0.30
	Sub-Elite	10	92.2	4.4	96.6	0.31 ± 0.05	0.01 ± 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

202 **Legend:** The mean loading coefficient is expressed with its standard deviation. NL= no load barefoot kick, WL1
 203 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg;
 204 WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 15kg; WL4 = 45kg - 2 kg military
 205 boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg.
 206

207

208 There was a marked similarity between elite and sub-elite subjects in terms of the PC1 scores
209 multiplied by the mean loading coefficient (Figure 2). For NL and WL4, the interval of the
210 PC1 score for the elite subjects defined by the mean \pm 1 standard deviation fell within the
211 equivalent interval for the sub-elite subjects across all time points. The same was true for WL2
212 prior to and during contact, however, after contact the elite subjects exhibited more knee
213 flexion for WL2. A full set of PC1 and PC2 scores for both knee and hip angles for all
214 conditions are presented in the Supplementary Web Content (Supplementary Figures 1 and 2).
215

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

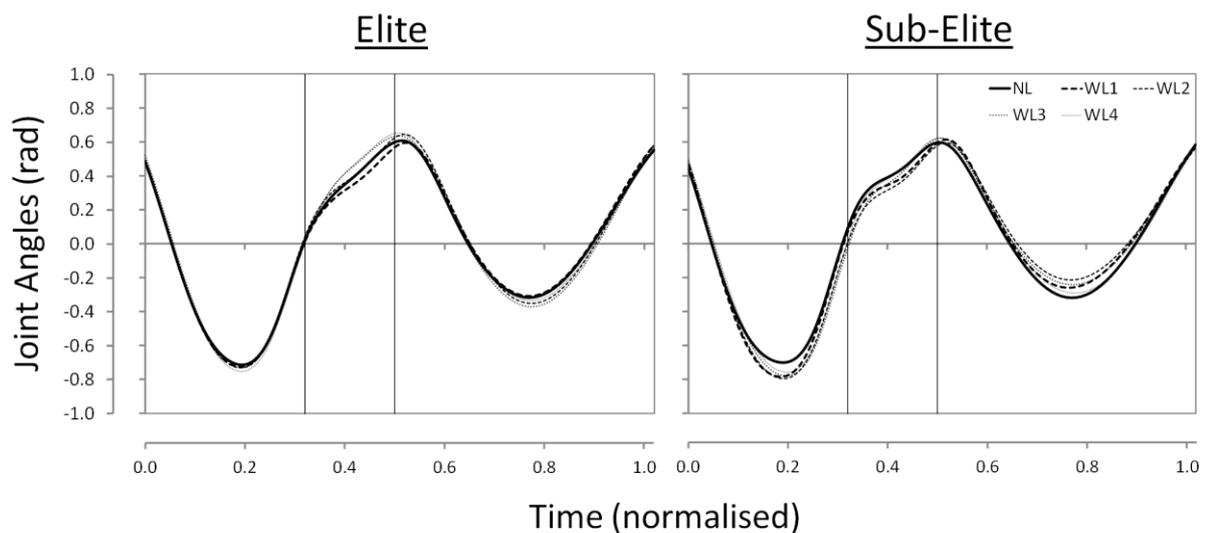


218
 219 **Legend:** NL= no load barefoot kick; WL2 = 15kg – military boots 2 kg, rifle 3 kg and ballistic vest 10 kg; WL4
 220 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg. Thinner lines indicate PC scores
 221 multiplied by mean loading coefficients ± 1 standard deviation. Vertical lines at $t = 0.32$ and $t = 0.5$ indicate the
 222 contact period during the kick. Joint angles are centred around the mean joint angle and more positive values are
 223 indicative of joint extension.

224
 225 When comparing across conditions, for the elite subjects, there was very little difference in the
 226 PC1 scores multiplied by the mean loading coefficients prior to contact, whereas the sub-elite

227 subjects exhibited greater knee flexion prior to contact during the weighted conditions as
 228 compared to NL (Figure 3). After contact, the elite subjects tended to exhibit greater knee
 229 flexion in the weighted conditions, whereas in contrast, the sub-elite subjects exhibited reduced
 230 knee flexion.

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



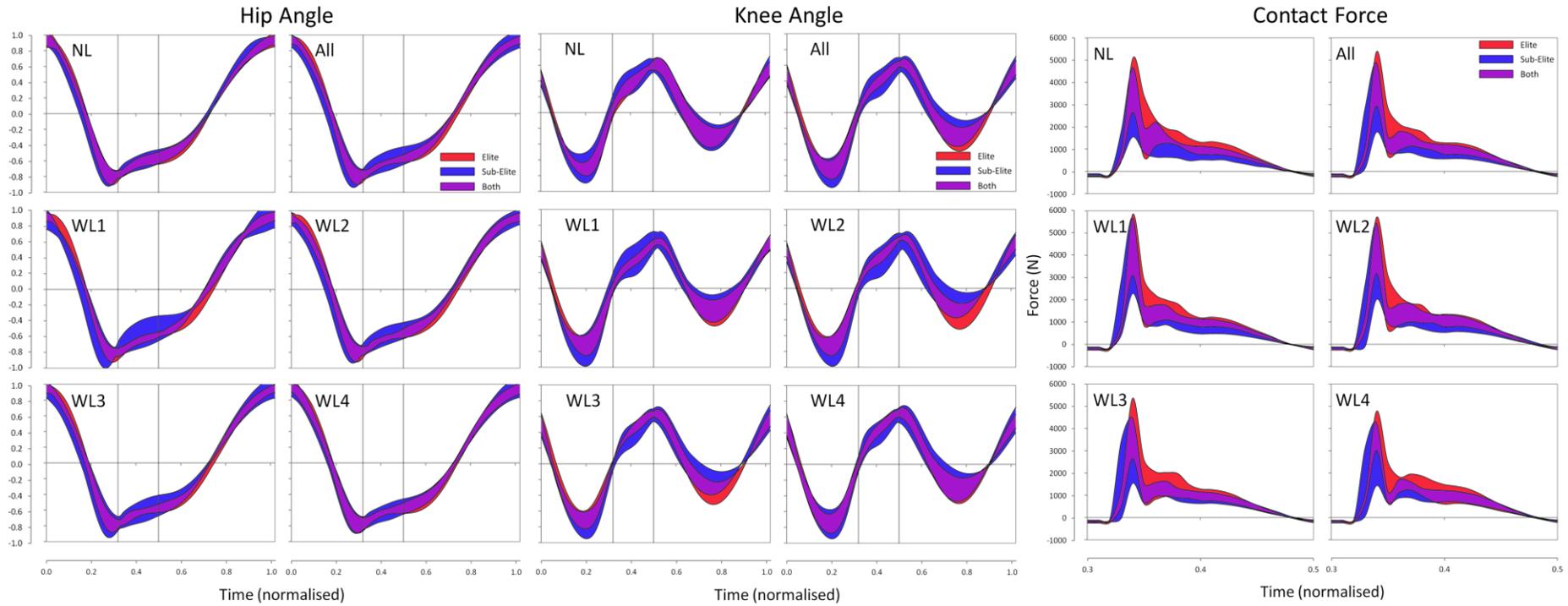
233
 234 **Legend:** NL= no load barefoot kick, WL1 = 5kg - military boots 2 kg and rifle 3 kg; WL2 = 15kg – military boots
 235 2 kg, rifle 3 kg and ballistic vest 10 kg; WL3 = 30kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back
 236 pack 15kg; WL4 = 45kg - 2 kg military boots, rifle 3 kg, ballistic vest 10 kg and back pack 30kg. Thinner lines
 237 indicate PC scores multiplied by mean loading coefficients ± 1 standard deviation. Vertical lines at $t = 0.32$ and t
 238 $= 0.5$ indicate the contact period during the kick. Joint angles are centered around the mean joint angle and more
 239 positive values are indicative of joint extension.

240
 241 Figure 4 illustrates the variation in the sum of the scores for PC1 and PC2 for knee and hip
 242 angles. For the NL condition, the variation in scores was smaller for the elite subjects and the
 243 range of scores for the elite subjects again largely fell within the range of the sub-elite subjects.
 244 However, for the weighted conditions the sum of the scores did not coincide so closely, and
 245 the elite subjects showed more knee and hip flexion post contact. For knee angle, the
 246 differences between the two groups were largest for WL2 and WL3, whereas for hip angle the
 247 difference was largest for WL1. Figure 4 also indicates that the elite subjects expressed a

248 greater contact force during the duration of the kick and a greater rate of force development in
249 the early part of the contact phase.

250

251 **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
 252 coefficients ± 1 standard deviation for elite and sub-elite subjects during kicking across a range of conditions.



253

254 **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
 255 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
 256 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
 257 centered around the mean joint angle and more positive values are indicative of joint extension.

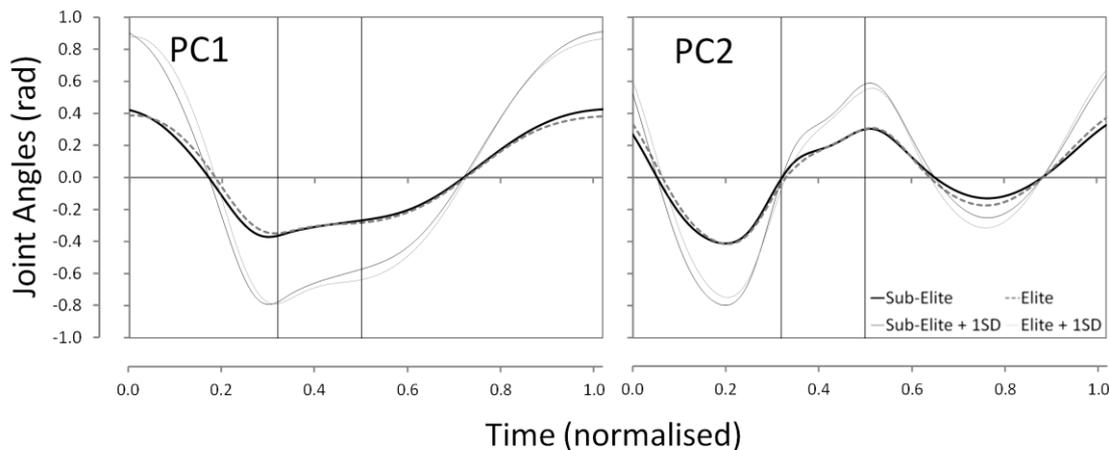
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260

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

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



267
 268 **Legend:** Thinner lines indicate PC scores multiplied by mean loading coefficients + 1 standard deviation. Vertical
 269 lines at $t = 0.32$ and $t = 0.5$ indicate the contact period during the kick. Joint angles are centred around the mean
 270 joint angle.

271 **Table 3.** Within and between individual and between joint variability in knee and hip angles
 272 explained by principal components (PCs) 1 and 2 during kicking by elite and sub-elite
 273 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

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

277 The individual level analysis also demonstrated that PC1 explained a greater proportion of the
 278 mean within individual variability for the elite subjects for all variables (Table 4). These
 279 differences were statistically significant and of large effect size for hip angle ($p = 0.009$, $d =$
 280 1.02) and contact force ($p = 0.003$, $d = 1.13$).

281 **Table 4.** Mean within individual variability explained by principal components (PCs) 1 and 2
 282 for knee and hip angle and contact force during kicking by elite and sub-elite subjects. Principal
 283 component analysis was performed separately for each individual and variable but included all
 284 conditions. Note that for the combined knee and hip angle analysis the variability derives from
 285 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

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

287

288 Discussion

289 The purpose of this study was to use PCA to analyse the differences in the movement strategies
 290 employed by elite and sub-elite subjects when performing a kicking task across a range of
 291 conditions. Overall, the variability in hip and knee angles explained by PC1 is greater for elite
 292 subjects and the dispersion of the loading coefficient for PC1 is also lower for the elite subjects
 293 (Table 2). Taken together, these observations indicate that there was much less within and
 294 between subject variation in the movement strategy employed by the elite subjects when
 295 compared to their sub-elite counterparts. As the magnitude of the difference in the within
 296 subject variability seen in the individual analysis was smaller than for the group analysis (even

297 taking into account that the individual analysis included all conditions; Table 4) this suggests
298 that there was less between subject variability in the elite subjects. This trend was seen despite
299 there being much greater variability in the ages of the elite subjects. Although this main result
300 is in agreement with the basic motor control presumption of increasing movement precision
301 with increased skill (Stergiou & Decker, 2011), there is also evidence of an increased
302 possibility of precise movement variations in more experienced athletes across different PPE
303 conditions (Bernstein, 1967). The substantial differences between the elite and sub-elite
304 subjects across conditions are discussed below.

305 The example in Figure 2 and Supplementary Figure 1 indicates that for the NL condition, the
306 weighted PC1 scores for knee and hip angle for the two groups were qualitatively similar for
307 both elite (knee 95.2%, hip 99.0%) and sub-elite subjects (knee 93.6%, hip 98.3). This indicates
308 that there was a fundamental characteristic pattern of knee and hip angle over time that was
309 remarkably similar between the two groups, where the groups differed in the dispersion of the
310 PC1 scores as expressed by the standard deviation of the loading coefficients. As can be seen
311 in Figure 2 and Supplementary Figure 1, this was much greater for the sub-elite group,
312 indicating that although the pattern was similar at a group level, there was more inter-individual
313 variation when it came to the relative magnitudes of knee and hip flexion and extension during
314 the movement. In contrast, for PC2 the standard deviation of the loading coefficient for the
315 elite group was greater and the dispersion of the PC2 scores much more similar. This finding
316 seems to be contradictory to the presumption that elite level athletes have a large specificity of
317 their movements resulting in functionality by movement variability (Bartlett et al., 2007;
318 Preatoni et al., 2013), which has been shown in a golf swing (Tucker et al., 2013) or basketball
319 shot (Wagner et al., 2012). However, it is important to note that here we are reporting the single
320 joint variability and not the joint coupling strategy, and thus we can suggest that as skill
321 increases the single joint pattern is more stable. We would advance the following speculative

322 explanation for these observations. It would seem that the PC1 score represents a characteristic
323 pattern that is exhibited within a front kick of this type, and that as skill increases there is less
324 variation between the executors in this pattern – it becomes more stable. To use the language
325 of dynamic systems theory, this is an attractor state. The loading coefficients simply represent
326 a scaling factor that changes the magnitude of the curve, and thus the standard deviations of
327 the loading coefficients don't represent any variation in the nature of the pattern apart from its
328 relative size. Instead, for any particular trial, the principal mode of variation from the attractor
329 state is described by the PC2 score. For the NL condition, the pattern of this variation was
330 markedly similar between the two groups and the dispersion across individuals was of the same
331 order of magnitude. That is, for the PC2 score, increasing skill level does not meaningfully
332 decrease the variation.

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

347 demands, it does so in a similar way for both groups, and the movement of the elite subjects
348 resembles that of their sub-elite counterparts.

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

361 Figure 4 presents the dispersion of possible values of knee and hip angles (within one standard
362 deviation of the mean loading coefficient) of the sum of the weighted PC1 and PC2 scores. For
363 NL, the elite group's performance largely lies centrally within the range of values seen in the
364 sub-elite group. Across the first three weighted conditions, there is some deviation in the
365 performance of the task between the two groups. The largest variation is seen post contact in
366 WL2, where the elite group exhibits greater peak knee flexion which occurs later in the phase.
367 We suggest this represents the greater skill level of the elite subjects in using a more appropriate
368 movement strategy, as the elite group exhibited higher force magnitude with higher force
369 gradient for all loading conditions during the contact phase (Figure 4). For WL4, there is much
370 less deviation between the two groups, which we suggest is a result of the elite group's

371 performance beginning to break down under the more demanding task constraints, and thus
372 starting to approximate the less skilled performance of the sub-elite group. The same trends
373 across weighted conditions can be seen in terms of the hip angle (Figure 4) – that is, the
374 movement patterns for the two groups were most similar for NL and WL4.

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

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

393

394

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398 **References**

- 399 Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports
400 biomechanists? *Sports Biomechanics*, 6(2), 224–243.
401 <https://doi.org/10.1080/14763140701322994>
- 402 Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Pergamon Press.
403 <http://www.citeulike.org/group/532/article/1220109>
- 404 Betzler, N. F., Monk, S. A., Wallace, E. S., & Otto, S. R. (2012). Variability in clubhead
405 presentation characteristics and ball impact location for golfers' drives. *Journal of*
406 *Sports Sciences*, 30(5), 439–448.
- 407 Borzelli, G., Cappozzo, A., & Papa, E. (1999). Inter- and intra-individual variability of
408 ground reaction forces during sit-to-stand with principal component analysis. *Medical*
409 *Engineering & Physics*, 21(4), 235–240. [https://doi.org/10.1016/s1350-](https://doi.org/10.1016/s1350-4533(99)00050-8)
410 [4533\(99\)00050-8](https://doi.org/10.1016/s1350-4533(99)00050-8)
- 411 Bradshaw, E. J., Maulder, P. S., & Keogh, J. W. (2007). Biological movement variability
412 during the sprint start: Performance enhancement or hindrance? *Sports Biomechanics*,
413 6(3), 246–260.
- 414 Cleather, D. J., & Cushion, E. J. (2019). Muscular coordination during vertical jumping.
415 *Journal of Human Performance and Health*, 1, a1-10.
- 416 Cleather, D. J., Goodwin, J. E., & Bull, A. M. J. (2013). Inter-segmental moment analysis
417 characterises the partial correspondence of jumping and jerking. *Journal of Strength*
418 *and Conditioning Research*, 27, 89–100.
419 <https://doi.org/10.1519/JSC.0b013e31825037ee>
- 420 Cushion, E. J., Warmenhoven, J., North, J., & Cleather, D. J. (2019). Principal component
421 analysis reveals the proximal to distal pattern in vertical jumping is governed by two

422 functional degrees of freedom. *Frontiers in Bioengineering and Biotechnology*, 7,
423 193.

424 Cushion, E. J., Warmenhoven, J., North, J., & Cleather, D. J. (2020). Task demand changes
425 motor control strategies in vertical jumping. *Journal of Motor Behavior*, *in press*.

426 Daffertshofer, A., Lamoth, C. J. C., Meijer, O. G., & Beek, P. J. (2004). PCA in studying
427 coordination and variability: A tutorial. *Clinical Biomechanics (Bristol, Avon)*, 19(4),
428 415–428. <https://doi.org/10.1016/j.clinbiomech.2004.01.005>

429 Deluzio, K. J., & Astephen, J. L. (2007). Biomechanical features of gait waveform data
430 associated with knee osteoarthritis: An application of principal component analysis.
431 *Gait & Posture*, 25(1), 86–93.

432 Fleisig, G., Chu, Y., Weber, A., & Andrews, J. (2009). Variability in baseball pitching
433 biomechanics among various levels of competition. *Sports Biomechanics*, 8(1), 10–
434 21.

435 Kuragano, T., & Yokokura, S. (2012). Experimental Analysis of Japanese Martial Art Nihon-
436 Kempo. *ICHPER-SD Journal of Research*, 7(1), 40–45.

437 LaGoy, A. D., Johnson, C., Allison, K. F., Flanagan, S. D., Lovalekar, M. T., Nagai, T., &
438 Connaboy, C. (2020). Compromised Dynamic Postural Stability Under Increased
439 Load Carriage Magnitudes. *Journal of Applied Biomechanics*, 36(1), 27–32.

440 Lust, K. R., Sandrey, M. A., Bulger, S. M., & Wilder, N. (2009). The effects of 6-week
441 training programs on throwing accuracy, proprioception, and core endurance in
442 baseball. *Journal of Sport Rehabilitation*, 18(3), 407–426.

443 Moreira, P. V. S., Falco, C., Menegaldo, L. L., Goethel, M. F., de Paula, L. V., & Gonçalves,
444 M. (2020). Are isokinetic leg torques and kick velocity reliable predictors for
445 competitive success in taekwondo athletes? *BioRxiv*.

446 Müller, H., & Sternad, D. (2004). Decomposition of variability in the execution of goal-
447 oriented tasks: Three components of skill improvement. *Journal of Experimental*
448 *Psychology: Human Perception and Performance*, 30(1), 212.

449 Newell, K. M., Broderick, M. P., Deutsch, K. M., & Slifkin, A. B. (2003). Task goals and
450 change in dynamical degrees of freedom with motor learning. *Journal of*
451 *Experimental Psychology: Human Perception and Performance*, 29(2), 379.

452 Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., Van Emmerik, R. E. A., Wilson, C., &
453 Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports*
454 *Biomechanics*, 12(2), 69–92. <https://doi.org/10.1080/14763141.2012.738700>

455 Richter, C., O'Connor, N. E., Marshall, B., & Moran, K. (2014). Comparison of discrete-
456 point vs. Dimensionality-reduction techniques for describing performance-related
457 aspects of maximal vertical jumping. *Journal of Biomechanics*, 47(12), 3012–3017.
458 <https://doi.org/10.1016/j.jbiomech.2014.07.001>

459 Rosenblatt, N. J., Hurt, C. P., Latash, M. L., & Grabiner, M. D. (2014). An apparent
460 contradiction: Increasing variability to achieve greater precision? *Experimental Brain*
461 *Research*, 232(2), 403–413. <https://doi.org/10.1007/s00221-013-3748-1>

462 Sørensen, H., Zacho, M., Simonsen, E. B., Dyhre-Poulsen, P., & Klausen, K. (1996).
463 Dynamics of the martial arts high front kick. *Journal of Sports Sciences*, 14(6), 483–
464 495.

465 Scholz, J. P., & Schöner, G. (1999). The uncontrolled manifold concept: Identifying control
466 variables for a functional task. *Experimental Brain Research*, 126(3), 289–306.

467 Scholz, J. P., Schöner, G., & Latash, M. L. (2000). Identifying the control structure of
468 multijoint coordination during pistol shooting. *Experimental Brain Research*, 135(3),
469 382–404.

- 470 Schöner, G., Zanone, P. G., & Kelso, J. A. S. (1992). Learning as change of coordination
471 dynamics: Theory and experiment. *Journal of Motor Behavior*, 24(1), 29–48.
- 472 Schorer, J., Baker, J., Fath, F., & Jaitner, T. (2007). Identification of interindividual and
473 intraindividual movement patterns in handball players of varying expertise levels.
474 *Journal of Motor Behavior*, 39(5), 409–421.
- 475 Seidler, R. D. (2010). Neural Correlates of Motor Learning, Transfer of Learning, and
476 Learning to Learn. *Exercise and Sport Sciences Reviews*, 38(1), 3–9.
477 <https://doi.org/10.1097/JES.0b013e3181c5cce7>
- 478 Seifert, L., Leblanc, H., Herault, R., Komar, J., Button, C., & Chollet, D. (2011). Inter-
479 individual variability in the upper–lower limb breaststroke coordination. *Human*
480 *Movement Science*, 30(3), 550–565.
- 481 Stastny, P., Maszczyk, A., Tománková, K., Kubový, P., Richtrová, M., Otáhal, J., Čichoň, R.,
482 Mostowik, A., Źmijewski, P., & Ciężczyk, P. (2015). Kinetic and kinematic
483 differences in a golf swing in one and both lower limb amputees. *Journal of Human*
484 *Kinetics*, 48(1), 33–41.
- 485 Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and
486 pathology: Is there a connection? *Human Movement Science*, 30(5), 869–888.
- 487 Tucker, C. B., Anderson, R., & Kenny, I. C. (2013). Is outcome related to movement
488 variability in golf? *Sports Biomechanics*, 12(4), 343–354.
489 <https://doi.org/10.1080/14763141.2013.784350>
- 490 Vagner, M., Cleather, D. J., Kubovy, P., Hojka, V., & Stastny, P. (2020). Kinematic
491 determinants of front kick dynamics across different loading conditions. *Under*
492 *Review*.

493 Vagner, M., Malecek, J., Hojka, V., Kubovy, P., & Stastny, P. (2020). A carried military load
494 increases the impact force and time of a front kick but reduces the peak velocity of the
495 hip and shoulder of the kicking leg. *ARCHIVES OF BUDO*, *16*, 69–76.

496 Wagner, H., Pfusterschmied, J., Klous, M., von Duvillard, S. P., & Müller, E. (2012).
497 Movement variability and skill level of various throwing techniques. *Human*
498 *Movement Science*, *31*(1), 78–90. <https://doi.org/10.1016/j.humov.2011.05.005>

499 Wilson, C., Simpson, S. E., Van Emmerik, R. E., & Hamill, J. (2008). Coordination
500 variability and skill development in expert triple jumpers. *Sports Biomechanics*, *7*(1),
501 2–9.

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