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AVERAGE OF TRIAL PEAKS VERSUS PEAK OF AVERAGE PROFILE: IMPACT ON CHANGE OF DIRECTION BIOMECHANICS

Original Research

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1 **ABSTRACT**

2 The aims of this study were twofold: firstly, to compare lower limb kinematic and kinetic

3 variables during a sprint and 90° cutting task between two averaging methods of obtaining

4 discrete data (peak of average profile vs average of individual trial peaks); secondly, to

5 determine the effect of averaging methods on participant ranking of each variable within a

6 group. Twenty-two participants, from multiple sports, performed a 90˚ cut, whereby lower

7 limb kinematics and kinetics were assessed via 3D motion and ground reaction force (GRF)

8 analysis. Six of the eight dependent variables (vertical and horizontal GRF; hip flexor, knee

9 flexor, and knee abduction moments, and knee abduction angle) were significantly greater (p

10 ≤ 0.001, $g = 0.10$-0.37, 2.74-10.40%) when expressed as an average of trial peaks compared

11 to peak of average profiles. Trivial ($g \leq 0.04$) and minimal differences ($\leq 0.94\%$) were

12 observed in peak hip and knee flexion angle between averaging methods. Very strong

13 correlations ($\rho \geq 0.901$, $p < 0.001$) were observed for rankings of participants between

14 averaging methods for all variables. Practitioners and researchers should obtain discrete data

15 based on the average of trial peaks because it is not influenced by misalignments and

16 variations in trial peak locations, in contrast to the peak from average profile.

17 Word count: 2929

18 Key words: cutting, discrete data, statistical design, kinetics, kinematics

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23 **INTRODUCTION**

24 Change of directions (COD) are commonly associated with non-contact anterior cruciate

25 ligament injuries in sport (Koga et al., 2010; Olsen, Myklebust, Engebretsen, & Bahr, 2004).

26 Although the mechanisms of this injury are multifactorial (Quatman, Quatman-Yates, &

27 Hewett, 2010), lower limb and whole body postures are critical factors associated with knee

28 joint loading (Besier, Lloyd, Cochrane, & Ackland, 2001; Koga et al., 2010; Kristianslund,

29 Faul, Bahr, Myklebust, & Krosshaug, 2014; Olsen et al., 2004). Thus, screening athletes'

30 COD biomechanics via the gold standard method of 3D motion analysis (Fox, Bonacci,

31 McLean, Spittle, & Saunders, 2015) is of great interest to researchers and practitioners to 1)

32 identify the potential mechanisms of injury; 2) identify biomechanical deficits; and 3) risk

33 stratify athletes (Hewett, 2017; Mok & Leow, 2016).

34 Lower limb kinetics and kinematic variables including: peak knee abduction angle

35 (KAA), peak knee abduction moment (KAM), peak knee flexion angle, and peak vertical

36 ground reaction force (GRF) are commonly evaluated in athletic populations. These variables

37 have been reported in prospective research to be associated with ACL injury (Hewett et al.,

38 2005; Leppänen et al., 2017) and are also commonly observed characteristics of injury

39 (Hewett, 2017; Koga et al., 2010; Olsen et al., 2004). Potentially 'at-risk' athletes displaying

40 biomechanical deficits in these variables can be subsequently treated and rehabilitated to

41 reduce the relative risk of injury (Hewett, 2017; Mok & Leow, 2016).

42 Most COD biomechanical investigations include more than one trial to evaluate

43 biomechanical parameters (Dai et al., 2014; Dempsey, Lloyd, Elliott, Steele, & Munro, 2009;

44 Havens & Sigward, 2015; Sigward, Cesar, & Havens, 2015). Although practitioners may

45 examine COD biomechanics during the fastest trial or examine peak data, which potentially

46 represents the likely demands placed upon an athlete in the 'worst case scenario', evaluating

47 a single trial does not represent an athlete's typical and generalised movement (James,

48 Herman, Dufek, & Bates, 2007). Moreover, single trial protocols have been suggested to be

49 invalid and unreliable which could lead to erroneous conclusions (Bates, Dufek, & Davis,

50 1992; James et al., 2007). As such, practitioners and researchers average biomechanical

51 parameters across multiple trials to represent an athlete's generalised and typical movement.

52 However, one issue in evaluating kinematic and kinetics via 3D motion analysis is the

53 method of analysing and obtaining discrete data from specific events (i.e. maximum or

54 minimum values during weight acceptance), and whether to obtain discrete data from the

55 peak of an average curve/profile or to average the individual trial peaks. Recently, Dames,

56 Smith, and Heise (2017) demonstrated angular velocity ($p < 0.001$, *ES* = 0.08-0.16, 1.1-2.2%)

57 and initial vertical GRF ($p = 0.002$, *ES* = 0.09, 0.9%) peak values from the average profile

58 were significantly lower compared to averaging trial peaks during walking gait (1.5 m/s). The

59 authors subsequently recommended parameters should be obtained from averaging trial peaks

60 compared to peak of average profile for a better representation of the data. To our knowledge,

61 no averaging recommendations exist for obtaining COD parameters.

62 Unfortunately, it remains unclear in the COD biomechanical literature how

63 researchers derive discrete data as several studies state trials were averaged (Besier et al.,

64 2001; Havens & Sigward, 2015; Sigward et al., 2015), but do not delineate whether a peak of

65 an average profile or average of trials peaks method was used. Additionally, some studies fail

66 to state whether average data was used for statistical analysis (Dai et al., 2016; Dai et al.,

67 2014; Dempsey et al., 2009). This is concerning because failing to state averaging procedures

68 makes it difficult to facilitate methodological replication, and if different outcome values are

69 produced between averaging methods, this could lead to different evaluations and diagnoses

70 in clinical and laboratory environments.

71

72   The aims of this study were twofold: firstly, to compare lower limb kinematic and

73   kinetic variables during a sprint and 90° cutting task between two averaging methods of

74   obtaining discrete data (peak of average profile vs average of individual trial peaks);

75   secondly, to determine the effect of averaging methods on participant ranking of each

76   variable within a group. It was hypothesised that different values would be produced between

77   the two averaging methods; however, there would be minimal differences in the ranking of

78   athletes.

79   **METHODS**

80   ***Participants***

81   Twenty-two (15 male and 7 female age: 23.2 ± 4.4 years, mass: 74.9 ± 12.8 kg, height: $1.75 \pm$

82   0.09 m) athletes from multiple sports (soccer n=11, rugby n=4, netball n= 5, cricket n=2)

83   participated in this study, which was greater than the sample size (n=12) used by Dames et al.

84   (2017) who examined the effect of averaging method on walking gait outcomes. The

85   investigation was approved by the University of Salford institutional ethics review board, and

86   all participants provided written informed consent. All participants performed a 5-minute

87   warm up consisting of jogging, self-selected dynamic stretching, and familiarisation trials of

88   the 90° cuts (4 trials performed submaximally at 75% of perceived maximal effort); similar to

89   the warm up procedures utilised in previous studies (Dai et al., 2014; Vanrenterghem,

90   Venables, Pataky, & Robinson, 2012).

91

92   ***Experimental protocol***

93   Lower limb kinematic and kinetic data were collected during a 90° cut to the left (5 m entry

94   and 3 m exit – push off right leg), performed as fast as possible (completion time 2.07 ± 0.09

95   seconds), on an indoor track (Mondo, SportsFlex, 10 mm; Mondo America Inc., Mondo,

96   Summit, NJ, USA). Participants performed a minimum of three acceptable trials (Mok, Bahr,

97   & Krosshaug, 2017). If the participants slid, turned prematurely, or missed the force platform,

98   the trial was discarded and subsequently another trial was performed after two minutes rest.

99   The procedures were based on previously published protocols (Jones, Herrington, &

100 Graham-Smith, 2016; Jones, Thomas, Dos'Santos, McMahon, & Graham-Smith, 2017), thus

101 a brief overview is provided. Prior to the cutting task, reflective markers (14 mm spheres)

102 were placed on bony landmarks of each participant (Jones et al., 2016; Jones et al., 2017).

103 Each participant wore a 4-marker ''cluster set'' (4 retroreflective markers attached to a

104 lightweight rigid plastic shell) on the right and left thigh and shin which approximated the

105 motion of these segments during the dynamic trials. All participants wore lycra shorts and

106 female participants wore a compression top (Champion Vapor, Champion, Winston-Salem,

107 NC, USA). Standardised footwear (Balance W490, New Balance, Boston, MA, USA) was

108 provided for all participants to control for shoe-surface interface.

109 ***Data analysis***

110 Three dimensional motions of these markers were collected during the cutting trials

111 using 10 Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz) operating

112 through Qualisys Track Manager software (Qualisys, version 2.16, build 3520, Gothenburg,

113 Sweden). The GRF's were collected from one 600 mm × 900 mm AMTI (Advanced

114 Mechanical Technology, Inc, Watertown, MA, USA) force platform (Model number:

115 600900) embedded into the running track sampling at 1200 Hz. From a standing trial, a lower

116 extremity and trunk 6 degrees of freedom kinematic model was created for each participant,

117 including pelvis, thigh, shank, and foot using Visual 3D software (C-motion, version 6.01.12,

118 Germantown, USA). This kinematic model was used to quantify the motion at the hip, knee,

119 and ankle joints using a Cardan angle sequence x-y-z (Suntay, 1983). The local coordinate

120 system was defined at the proximal joint centre for each segment. The static trial position was

121   designated as the participant's neutral (anatomical zero) alignment, and subsequent kinematic

122   and kinetic measures were related back to this position. Segmental inertial characteristics

123   were estimated for each participant (Dempster, 1955). This model utilised a CODA pelvis

124   orientation (Bell, Brand, & Pedersen, 1989) to define the location of the hip joint centre. The

125   knee and ankle joint centres were defined as the mid-point of the line between lateral and

126   medial markers. Lower limb joint moments were calculated using an inverse dynamics

127   approach (Winter, 2009) through Visual 3D software and were defined as external moments.

128   Initial contact was defined as the instant after ground contact that the vertical GRF

129   was higher than 20 N, and end of contact was defined as the point where the vertical GRF

130   subsided past 20 N (Kristianslund et al., 2014). The weight acceptance phase was defined as

131   the instant of initial contact to the point of maximum knee flexion (Havens & Sigward,

132   2015). All joint moments, joint angles, and GRFs (see table 1 for dependent variables) were

133   derived during weight acceptance and used for further analysis. Using the pipeline function in

134   visual 3D, joint coordinate and force data were smoothed with a fourth-order Butterworth

135   low-pass digital filter with cut-off frequencies of 15 Hz and 25 Hz, based on *a priori* residual

136   analysis (Winter, 2009), visual inspection of motion data, and recommendations by Roewer,

137   Ford, Myer, and Hewett (2014).

138   An average magnitude of each dependent variable were derived using two methods

139   (Dames et al., 2017) and compared for statistical analysis. The first involved averaging the

140   individual trial peaks across three trials (average of trial peaks). The second involved creating

141   an average profile (normalised to 100% of weight acceptance) of three trials and obtaining a

142   single peak from the average profile (peak from average profile).

143   ***Statistical Analyses***

144   All statistical analysis was performed in SPSS v 23 (SPSS Inc., Chicago, IL, USA)

145   and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). Normality was

146 confirmed for all variables utilising a Shapiro-Wilks test. Within-session reliability was

147 assessed using intra class coefficients (ICC) and the standard error of measurement was

148 calculated using the formula: $SD(pooled) * \sqrt{(1 - \text{ICC})}$ (Thomas, 2005). Differences in

149 dependent variables between methods were assessed using paired sample t-tests, effect sizes,

150 mean differences (bias), and percentage differences. The 95% limits of agreement (LOA)

151 (LOA: mean of the difference ± 1.96 standard deviations) were also calculated between

152 averaging methods using methods described by Bland and Altman (1986). All data was

153 visually inspected using Bland-Altman plots to confirm homoscedasticity. Hedges' g effect

154 sizes were calculated as described previously (Hedges & Olkin, 1985) and interpreted using

155 Hopkins' (2002) scale. To assess whether averaging method impacted the ranking of players

156 for each dependent variable, Spearman's correlations coefficients were also calculated.

157 Statistical significance was defined $p \leq 0.05$ for all tests.

158 **RESULTS**

159 Mean ± SD are presented for all dependent variables between averaging methods in Table 1.

160 All variables demonstrated high within-session reliability measures (ICC ≥ 0.863) and SEM

161 values ranged from 0.08-0.10 N/BW for GRF variables, 1.10-2.64° for joint angles, and 0.12-

162 0.23 Nm/kg for joint moments (Table 1).

163 Six of the 8 dependent variables (vertical and horizontal GRF, hip flexor, knee flexor,

164 and knee abduction moments, and knee abduction angle) were significantly greater when

165 expressed as an average of trial peaks compared to peak of average profiles, with trivial to

166 small effect sizes (g = 0.10-0.37) and mean percentage differences of 2.74-10.40% (Table 1),

167 respectively. Although a statistical, significant difference was observed in peak hip flexion

168 angle between the two averaging methods, effect sizes (g = 0.04) and percentage differences

169 (0.9%) indicated a trivial and minimal difference (Table 1). Similarly, a non-significant,

170   trivial, and minimal percentage difference (p = 0.279, g = 0.01, 0.09%) was observed in peak

171   knee flexion angle between averaging methods (Table 1). Very strong correlations ($\rho \geq 0.901$,

172   p < 0.001) were observed for rankings of participants between averaging methods for all

173   dependent variables (Table 2).

174   ***Insert Table 1 about here***

175   ***Insert Table 2 about here***

176   **DISCUSSION AND IMPLICATIONS**

177   The aims of this study were to examine the impact of averaging methods (peak of average

178   profile vs average of individual trial peaks) on commonly examined lower limb kinematic

179   and kinetic variables during cutting, and to determine the effect of averaging method on

180   participant ranking. The primary findings were significantly lower GRF, joint moments, and

181   KAA values were demonstrated when obtaining peak of average profile data compared to

182   average of trial peaks data (Table 1), supporting the study hypothesis. These results are in

183   line with the findings of Dames et al. (2017) that reported significantly lower angular velocity

184   (p < 0.001, ES = 0.08-0.16, 1.1-2.2%) and GRF (p = 0.002, ES = 0.09, 0.9%) data during

185   walking gait (1.5 m/s), based on peak of average profile data. Interestingly, the averaging

186   method had a trivial and minimal effect on sagittal plane joint angles (hip and knee flexion)

187   (Table 1). Additionally, very strong correlations were observed for participant ranking

188   between averaging methods for all dependent variables (Table 2), indicating an athlete will

189   most likely achieve the same ranking in a cohort of athletes, irrespective of the averaging

190   method used.

191   ***Insert Figure 1 about here***

192   The trivial to small, yet significantly lower values (2.74-10.40%) observed in the

193   present study for GRF, joint moment, and KAA (Table 1) variables could be attributed to

194   misalignments in the temporal profiles (variation in the location of peak data on the time

195   series) (Figure 1) (Dames et al., 2017). It is worth noting, however, that if trial peaks occur at

196   a similar point of the time-series (i.e. similar % of weight acceptance), then the differences

197   between averaging methods will be minimal, evident by the minimal differences observed for

198   peak hip and knee flexion angles in the present study (Table 1). Nevertheless, when the

199   individual trials are normalised to produce an average profile, the peak value from these

200   curves were on average 2.74-10.40% lower for GRF, joint moment, and KAA variables. The

201   subtle differences in values may lead to different evaluations and diagnoses in clinical and

202   laboratory environments; thus, researchers and practitioners are consequently recommended

203   to standardise the averaging method when longitudinally monitoring changes in COD

204   biomechanical parameters to allow valid comparisons. Furthermore, researchers are

205   recommended to clearly state their averaging method to facilitate methodological replication.

206   Future applied work could consider determining a phase shift to remove large outliers in the

207   data set (Dames et al., 2017).

208   ***Insert Figure 2 about here***

209   In contrast to Dames et al. (2017), that found greater magnitudes of differences for

210   kinematic (angular velocities) data than kinetic (GRF) data between averaging methods, the

211   present study found the largest effect sizes between averaging methods were present for GRF

212   data (Table 1, Figure 2). These opposing findings could be explained by Dames et al. (2017)

213   investigating walking gait which is lower in velocity compared to the present study and thus,

214   associated with lower GRF's, particularly horizontally. Additionally, cutting is a more

215   complex manoeuvre than walking, whereby the addition of higher entry velocity most likely

216   results in slightly different movements strategies at impact between trials, thus resulting in

217   temporal misalignments in peak GRF (Figure 2). Finally, it should be acknowledged that

218   joint angular velocities were the only kinematic variables examined by Dames et al. (2017),

219   whereas the present study examined peak joint angles over weight acceptance during cutting,

220   whereby sagittal plane joint angles hip and knee flexion demonstrated consistent temporal

221   alignments, thus minimal differences.

222   Caution is advised when using pre-defined thresholds in order to identify potentially

223   'at-risk' athletes for particular parameters which may be used to subsequently inform

224   training. For example, an athlete below an 'at-risk' threshold may not be classified as 'at risk'

225   for a particular variable based on peak of average profile data. Conversely, based on average

226   of trial peaks data the same athlete may have a greater value which subsequently classes them

227   as 'at-risk', and may therefore receive specific training or treatment. It could therefore, be

228   argued that the choice of averaging method could lead to different clinical diagnoses, and

229   may result in false negative/positive identification which could influence the future training

230   for that athlete. However, it is worth noting that very strong relationships were observed for

231   participant ranking between averaging methods for all dependent variables (Table 2),

232   indicating an athlete will most likely achieve the same ranking in a cohort of athletes,

233   irrespective of the averaging method used.

234   It is also worth acknowledging that standard deviations (variation) observed for

235   kinetic and kinetic variables (Table 1) were similar between averaging methods, in line with

236   the findings of Dames et al. (2017). Thus, it is likely that absolute reliability may be similar

237   between averaging methods based on standard deviation driven reliability measures. Further

238   research comparing the effect of these aforementioned averaging methods on between-

239   session reliability is warranted to confirm which method provides the best reliability and

240   most sensitive measures.

241   It should be noted that the present study has several limitations. Firstly, by averaging

242   trials, in essence, a mythical, never performed trial is created; however, this procedure is

243   commonly used within the COD literature (Besier et al., 2001; Havens & Sigward, 2015;

244   Jones et al., 2016; Jones et al., 2017; Sigward et al., 2015), and averaging trials is suggested

245   to be representative of a participant's typical movement (James et al., 2007). Secondly, while

246   it may be common practice to average parameters between trials, some researchers may

247   choose to evaluate the fastest trial (Kimura & Sakurai, 2013), or the trial displaying the

248   greatest biomechanical deficit (i.e. greatest KAM or KAA) may also be of interest, though

249   caution is advised when evaluating movement based on a single trial (Bates et al., 1992;

250   James et al., 2007).

251   **CONCLUSION**

252   In conclusion, the averaging method to obtain discrete data results in subtle

253   differences in values produced, with the peak from the average profile demonstrating lower

254   GRF, joint moment, and KAA values during cutting. Consequently, researchers and

255   practitioners are recommended to obtain discrete data based on an average of trial peaks

256   because it is not influenced by misalignments and variations in trial peak locations, in

257   contrast to the peak from average profile. However, with the respect to participant ranking,

258   minimal differences are present between averaging methods. Researchers and practitioners

259   are also recommended to standardise the averaging method when longitudinally monitoring

260   changes in COD biomechanics for screening and clinical purposes or making group

261   comparisons. Moreover, when publishing research, it is advocated that researchers clearly

262   state the averaging method implemented to facilitate methodological replication.

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265 **DISCLOSURE STATEMENT**

267 **ACKNOWLEDGEMENTS**

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Table 1. Comparisons in dependent variables between averaging methods

Variable	Average of trial peaks		Peak of average profile		p	g	Mean difference (Bias)		95% LOA		% difference		ICC	SEM
	Mean	SD	Mean	SD			Mean	SD	LB	UB	Mean	SD		
pk VGRF (N/BW)	2.55	0.44	2.39	0.40	<0.001	0.37	0.15	0.13	-0.11	0.42	5.93	5.12	0957	0.10
pk HGRF (N/BW)	-1.41	0.27	-1.33	0.25	<0.001	-0.30	-0.11	0.02	-0.21	0.05	5.58	4.08	0.933	
pk HFA (°)	47.52	10.0	47.07	9.95	0.001	0.04	0.45	0.54	-0.6	1.51	0.94	1.10	0.962	2.02
pk HFM (Nm/kg)	-2.65	0.91	-2.46	0.90	0.001	0.21	0.19	0.23	-0.63	0.25	7.31	8.37	0.941	
pk KFA (°)	59.77	6.44	59.73	6.50	0.279	0.01	0.04	0.19	-0.33	0.42	0.09	0.38	0.863	2.64
pk KFM (Nm/kg)	3.46	0.63	3.37	0.63	<0.001	0.15	0.09	0.09	-0.09	0.28	2.74	2.69	0.936	
pk KAA (°)	-8.16	8.09	-7.31	8.09	<0.001	-0.10	-0.86	0.92	-2.66	0.95	10.40	9.41	0.982	1.10
pk KAM (Nm/kg)	0.99	0.36	0.92	0.34	<0.001	0.20	0.07	0.07	-0.07	0.21	7.03	6.74	0.909	

Key: pk: Peak; VGRF: Vertical ground reaction force; HGRF: Horizontal ground reaction force; HFA: Hip flexion angle; HFM: Hip flexor moment; KFA: Knee flexion angle; KFM: Knee flexor moment; KAA: Knee abduction angle; KAM: Knee abduction moment; LOA: Limits of agreement; LB: Lower bound; UB: Upper bound; BW: Body weight; ICC: Intraclass correlation coefficient; SEM: Standard error of measurement

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Table 2. Spearman's correlations based on ranking of participants between averaging methods for dependent variables

Dependent variable	ρ	p value
pk VGRF	0.901	<0.001
pk HGRF	0.961	<0.001
pk HFA	0.997	<0.001
pk HFM	0.958	<0.001
pk KFA	1.000	<0.001
pk KFM	0.960	<0.001
pk KAA	0.983	<0.001
pk KAM	0.964	<0.001

Key: pk: Peak; VGRF: Vertical ground reaction force; HGRF: Horizontal ground reaction force; HFA: Hip flexion angle; HFM: Hip flexor moment; KFA: Knee flexion angle; KFM: Knee flexor moment; KAA: Knee abduction angle; KAM: Knee abduction moment

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