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Dos'Santos, T, Comfort, P and Jones, PA (2020) Average of trial peaks versus peak of average profile: impact on change of direction biomechanics. *Sports Biomechanics*, 19 (4). pp. 483-492. ISSN 1476-3141

DOI: <https://doi.org/10.1080/14763141.2018.1497197>

Publisher: Taylor & Francis

Version: Accepted Version

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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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Abstract word count: 200 words

Manuscript word count: 2929 words

Number of tables and figures: 2 Tables and 2 Figures

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.

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: $SD(pooled) * \sqrt{(1 - ICC)}$ (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 \pm 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 \pm SD are presented for all dependent variables between averaging methods in Table 1.
160 All variables demonstrated high within-session reliability measures ($ICC \geq 0.863$) 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.

263

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265 DISCLOSURE STATEMENT

266 No potential conflict of interest was reported by the authors

267 ACKNOWLEDGEMENTS

268 The authors confirm would like to thank the participants for participating in this study.

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Table 1. Comparisons in dependent variables between averaging methods

Variable	Average of trial peaks		Peak of average profile		<i>p</i>	<i>g</i>	Mean difference (Bias)		95% LOA		% difference		ICC	359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374
	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		
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

388