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- 1 **The influence of isokinetic trunk flexor and extensor strength on dynamic**
- 2 **balance in children**
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4 **Abstract**

5 This study assessed if trunk flexor and extensor strength were predictors of time to stability
6 (TTS) and centre of pressure (CoP) during hop and hold tasks in children. Seventeen boys
7 (age; 10.1 ± 1.6 years; height, 1.45 ± 0.11 m; mass, 26.7 ± 7.83 kg) undertook isokinetic
8 strength assessments of concentric and eccentric trunk flexors/extensors at $60^\circ \cdot s^{-1}$, and
9 anterior/medial hop tasks. Hierarchical multiple regressions determined if concentric and
10 eccentric trunk flexor/extensor peak torques predict TTS using a composite score ($Comp_x$
11 $Comp_y$ $Comp_z$) and CoP_x and CoP_y . Concentric trunk flexors were the strongest predictor for
12 *TTS $Comp_{xy}$* , with concentric flexion and eccentric extension predicting *TTS $Comp_y$* . All
13 muscle actions were also strong predictors for CoP_y during hop tasks. These findings have
14 implications for the assessment of trunk musculature strength and measures of postural
15 control within a young healthy population. The development of trunk musculature strength may
16 aid improvements in dynamic balance tasks in children, with implications for fall and injury risk.
17 To improve trunk musculature strength and the potential to maintain postural control, a
18 combination of concentric and eccentric exercises with other training modalities appears
19 relevant due to the increased relevance to the demands of balance maintenance.

20 **Key Words**

21 Trunk strength, dynamic balance, hop and hold, time to stability, motor performance

22 Introduction

23 It has been well established that muscular strength is an important factor in relation to health,
24 and also sporting performance in both adults (Ruiz et al. 2008; Eustace et al. 2017) and
25 children (Castro-Piñero et al. 2010; Wind et al. 2010; Eustace et al. 2020). Muscular strength
26 during childhood and early adolescence is associated with superior strength that spans into
27 adulthood (Ortega et al. 2008; El-Kotob et al. 2020), reiterating the need to assess muscular
28 strength at an early age. Greater muscular strength improves the ability to maintain balance
29 following sudden perturbation (Granacher et al. 2013; Muehlbauer et al. 2015). However,
30 previous findings are equivocal due to prior studies employing different methods to quantify
31 balance and muscular strength (Muehlbauer et al. 2015), particularly concerning the muscles
32 selected for strength assessment. It has been suggested that impaired muscular strength of
33 the trunk relates to poor balance and increased risk of falling (Jain et al. 2021). Numerous
34 studies have also quantified isokinetic concentric peak torques of the trunk flexors and
35 extensors in children and early adolescents (Müller et al. 2014; Bernard et al. 2014; Barczyk-
36 Pawelec et al. 2015), but these assessments do not consider the mechanical demands of
37 postural control. For instance, anterior displacement of an individual's centre of mass would
38 create an external flexor moment, meaning an opposite internal trunk extensor torque is
39 required to counteract this movement. As such, there appears a need to quantify the eccentric
40 torques of the trunk flexors and extensors to better align to the demands of postural control
41 during tasks. Moreover, as isokinetic strength assessments of the trunk musculature,
42 particularly eccentric assessments, are not commonly related to balance ability in children,
43 and, as motor-control and balance are not fully developed in children (Streepey and Angulo-
44 Kinzler, 2002; Falkerslev et al. 2013; Austad et al. 2017), there remains a need to ensure
45 children possess sufficient muscular strength to complete functional tasks.

46

47 One such functional task, such as hopping, have been used to assess dynamic balance ability
48 in both children and adults (Kamonseki et al. 2018; Warming et al. 2021; Wdowski et al. 2021).
49 Time to stabilisation (TTS) during the completion of hop and hold tasks have been commonly
50 used due to their reliability and association with lower limb injury (Shaw et al. 2008; Webster
51 & Gribble, 2010). In line with injury aetiology, hop and hold tasks are suggested also to be
52 performed in the frontal plane of motion due to increased lateral peak impact forces and knee
53 abduction moments when compared to anterior hopping directions (Davies et al. 2020). The
54 outcome measures from hop and hold testing also requires further consideration, such as TTS
55 during the completion of the task. As TTS only identifies how long the individual takes to
56 stabilise body weight on a force plate, it could be argued (as illustrated in Figure 1) that an
57 individual who has a larger bodyweight range (those with higher variability during quite stance)
58 during a hop and hold may stabilise quicker to those with a smaller bodyweight range (those
59 with a lower variability during the stance phase). However, the methods used to quantify both
60 trunk musculature strength and postural control in children require further exploration with
61 better mapping of these different assessment approaches than previously. Therefore, this
62 study assessed if trunk flexor and extensor strength was a predictor of TTS and centre of
63 pressure (CoP) displacement in the medial/lateral anterior/posterior planes during hop and
64 hold tasks in children. It was hypothesised that eccentric peak torques of the trunk flexors and
65 extensors when compared to concentric actions would better relate to measures of dynamic
66 balance during anterior and medial hop and hold tasks in children.

67 **Material and Methods**

68 Seventeen boys (age, 10.1 ± 1.6 years; height, 1.45 ± 0.11 m; mass, 26.7 ± 7.83 kg; maturity
69 offset: -3.07 ± 1.26 years) who were regularly engaged in grassroots soccer participated in
70 the study following institutional ethics approval, informed parental consent and child assent,
71 in line with the Declaration of Helsinki (1964). Stature and body mass were assessed to the
72 nearest 0.1cm and 0.1 kg, with the participants barefoot and wearing light clothing (t-shirt and
73 shorts) using a SECA stadiometer and scales (SECA Instruments Ltd, Hamburg,

74 Germany). The Moore (Moore et al. 2015) prediction equation was used to determine maturity
75 offset (defined as the time from peak height velocity) using measures of height and body
76 mass as a marker of biological maturation. A priori statistical power calculation for the study
77 sample size were based on alpha ($P = 0.05$), beta (statistical power = 0.80) and the number
78 of predictors/groups with a small effect size based on Cohen's D (0.20). As such, based on
79 these calculations, to achieve statistical power of ≥ 0.80 for all outcome variables associated
80 with the study, the number of participants required were $n = 99$ (please see limitations section
81 for more details). Participants were recruited from their primary schools, United Kingdom. All
82 parents completed a health screen questionnaire prior to participation. This requested
83 information related to any physical, cognitive or other issues that may prevent participation in
84 physical activity. Exclusion criteria included chronic disease (e.g., diabetes), injuries, muscular
85 deficits, cardiovascular impairments or diagnosis of any form of developmental disorder likely
86 to influence motor performance (i.e., developmental coordination disorder, dyspraxia,
87 dyslexia, Asperger's syndrome, and autism). The pre-screening questionnaire was also used
88 to confirm that children had normal vision and no auditory impairments which may affect
89 balance.

90 The procedures of the familiarisation trial replicated the experimental condition, conducted
91 48hrs apart. To control for circadian variation (Rae et al. 2015), testing was conducted at the
92 same time for both visits. Participants reframed from food 3hrs prior to each visit following a
93 48hr abstinence from exercise, where height and mass were determined. Prior to the start of
94 each trial, participants were required to complete a standardised 5-minute warm-up on a
95 stationary cycle ergometer (Monark, 824E, Sweden) at 60 W. Dynamic stretches were also
96 completed, which included 2 sets of 30 seconds exercises of: torso twists, side-to-side flexion
97 and standing toe stretches for 20 seconds for at a low intensity (3/10). Each participant then
98 completed a warm-up set prior to the maximal contractions that were recorded for further
99 analysis. This was 1 set 5 contractions, with the first 2 contractions being at 50% of perceived
100 maximum, and the remaining repetitions performed at 75% of perceived maximum. Isokinetic

101 strength assessment of the trunk musculature followed the hopping tasks to mitigate any
102 potential fatigue responses.

103 Measures of TTS and centre of pressure (CoP) were assessed using an anterior and medial
104 hop and hold task on the dominant limb (Sell, 2012). Limb dominance was defined as the foot
105 used to kick a ball. Participants were instructed to stand on two legs at distance of 40% of
106 body height from the centre of a 0.4 × 0.6m force platform (AMTI, AccuGait, Watertown, MA).
107 Each participant was instructed to hop forward (anterior hop) or to the right/left (medial hop)
108 over a 6-inch hurdle on to the force platform and land on the dominant limb, stabilise as quickly
109 as possible, and balance for 20s (Fransz et al. 2015). All participants executed the take-off
110 phase of the anterior and medial hops with both lower limbs and used the dominant side to
111 stabilise the body during the landing phase of the task. Moreover, the medial hops were
112 performed where the dominant lower limb was closest to the hurdle. Each participant
113 completed a minimum of three practice attempts before data collection. Trials were discarded
114 if participants utilised arm movement to help stabilise the trunk (Wdowski et al. 2021), and
115 when participants failed to provide full foot contact with the force plate. Three successful trials
116 were recorded and used for further analysis.

117 A Trunk Modular Component attached to a HUMAC® NORM™ isokinetic dynamometer
118 (HUMAC® NORM™) was used for concentric and eccentric strength assessments of the trunk
119 flexors and extensors conducted at 60°·s⁻¹, where participants were instructed to elicit 3
120 submaximal attempts, followed by 5 maximal contractions with 60 seconds rest (Karatas et al.
121 2002). During familiarization to the isokinetic strength assessment, participants were provided
122 with verbal encouragement such as 'push', 'pull', 'as hard as you can' with live feedback
123 provided on the device's monitor. This process was completed in a suitable time where
124 participants could suitably control the input arm and provide consistent torque values. No
125 performance feedback or instructions were provided during the experimental procedures due
126 to reported effects on isokinetic torque (Campenella et al. 2000; Marchant et al. 2009). The
127 range of motion (ROM) of the hip joint was set at 0-45° (0° = full extension; standing position),

128 and gravity corrected at 45° of trunk flexion to better account for differing levels of muscle
129 stiffness in individuals at increased angles (excessive hip flexion in this case). Range of motion
130 was limited to 45° of trunk flexion to isolate the musculature and not engage the hips. This is
131 in accordance previous observations that suggest excessive hip flexion during trunk exercises
132 may result in an increased activity of the hip flexor musculature (Andersson et al. 1997;
133 Sullivan et al. 2015). Participants held the downward-facing handle in front of the chest to
134 prevent motion of the upper limbs. Restricting upper body motion and stabilising the lower
135 body were performed to avoid extraneous movements and minimize the unwanted
136 contribution of muscles not being tested. The heels were placed into the cup of standing plate,
137 with the height of the thigh stabiliser adjusted until the pads were behind the knees. The
138 footplate of the trunk module was raised until the rubber alignment point was opposite L5,
139 which was 3-5cm below the top of the iliac crest (the alignment of the axis of rotation of the
140 trunk module to the participant). Two cuff pads were placed above and below the knees with
141 firm pressure to ensure no movement of the lower limbs during the completion of the strength
142 assessment. Straps were then placed around the waist and scapula pad to secure the trunk
143 of the participant and adjusted accordingly for appropriate tension. While standing with a
144 neutral spine, the participant's anatomical zero position was determined as an angle of 0°
145 between the trunk and thighs. Mechanical stoppers were applied as a safety precaution.

146

147 Isokinetic peak torques that elicited the highest values were used for further analysis, along
148 with the corresponding angle of peak torque. The isokinetic peak torques were then used to
149 calculate strength ratios of the thigh musculature to demonstrate additional means to quantify
150 trunk stability with strength data. The following strength ratios were calculated based on
151 previous literature: 1; concentric trunk flexion/concentric trunk extension. 2; eccentric trunk
152 flexion and eccentric trunk extension. 3; concentric trunk flexion and eccentric trunk extension.
153 4; eccentric trunk flexion and concentric trunk extension. Force data were sampled at 1000
154 Hz and data were passed through a 4th order low pass Butterworth filter with a 20 Hz cut-off

155 frequency prior to statistical analysis. Force data exhibited during the completion anterior and
156 medial hopping tasks were used to calculate time to stability (TTS) using a composite score
157 ($Comp_x Comp_y Comp_z$) and CoP_x and CoP_y during the stance phase of movement. F_x (medial
158 lateral force), F_y (anterior posterior force) and F_z (vertical force) were used to determine TTS
159 (ms) in each respective plane. As per previous work (Fransz et al. 2015), mean and SD F_x ,
160 F_y and F_z during the last 500ms of the trial was calculated and upper and lower bounds for
161 stabilisation in each direction determined as $3*SD$ above or below the mean force. Stability
162 was determined in each plane as the point in which force fell within these bounds for at least
163 500ms. This creates an issue when the intention is to make comparisons between individuals
164 given that those that are capable of minimising postural disturbances during single leg stance
165 have smaller TTS boundaries, potentially resulting in misleading outcomes (Figure 1). To
166 overcome this, a TTS composite score was determined by multiplying the TTS (s) by the
167 magnitude of the calculated bound (N), where a lower value represents better balance
168 performance. CoP coordinates were used to determine the maximal medial-lateral and
169 anterior-posterior displacement over a 2.5s period following initial contact. Time was
170 standardised so that the duration of the test did not influence the results. 2.5s captures mean
171 TTS for each plane across both tasks. Initial contact was defined as the first F_z data point that
172 exceeded 10N. An average TTS for the three trials and respective hopping direction were
173 calculated and used for statistical analysis.

174 ***Insert figure 1 here***

175 Hierarchical multiple regressions were conducted to determine if the addition of concentric
176 and eccentric trunk flexion and extension accounted for more variation of balance during
177 anterior and medial hopping tasks. The specific ordering of the analysis were: concentric
178 flexion (Model 1), concentric extension (Model 2), eccentric flexion (Model 3), eccentric
179 extension (Model 4), concentric flexion and eccentric extension (Model 5), eccentric flexion
180 and concentric extension (Model 6), concentric flexion and concentric extension (Model 7),
181 eccentric flexion and eccentric extension (Model 8), and all muscle actions (Model 9). All

182 assumptions for hierarchical multiple regressions were assessed. For the strength ratio data,
183 concentric trunk flexion/concentric trunk extension (Model 10), eccentric trunk flexion and
184 eccentric trunk extension (Model 11), concentric trunk flexion and eccentric trunk extension
185 (Model 12), eccentric trunk flexion and concentric trunk extension (Model 13) were also
186 analysed. There was linearity as assessed by partial regression plots and a plot of studentized
187 residuals against the predicted values. There was independence of residuals, as assessed by
188 a Durbin-Watson statistic of ~ 2.00 . There was homoscedasticity, as assessed by visual
189 inspection of a plot of studentized residuals versus unstandardized predicted values. There
190 was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. There
191 were no studentized deleted residuals greater than ± 3 standard deviations, no leverage values
192 greater than 0.2, and values for Cook's distance above 1. The assumption of normality was
193 met, as assessed by Shapiro-Wilk's test. The strength of the relationship and to account for
194 variance (R^2) was defined as small (≤ 0.12), medium (0.13 – 0.25) and large (≥ 0.26) (Cohen,
195 1992). Pearson's correlations were conducted to assess the relationship between $TTS Comp_x$
196 $Comp_y$ $Comp_z$ and CoP_x and CoP_y for anterior and medial hopping directions. The
197 measurement error of all data associated with this study was determined using the standard
198 error of measurement (SEM). The SEM was calculated as the standard deviation of the test
199 metric, multiplied by the square root of a correlation coefficient of 1, minus the correlation
200 coefficient of the test. All statistical tests were conducted in R (R Core Team, 2022; Version
201 4.2.2, Boston, US) with significance set at $P \leq 0.05$.

202 **Results**

203 Tables 1 and 2 summarise the descriptive statistics and SEM of all outcome variables
204 associated with the present study, respectively. These observations suggest the SEM for
205 these outcome variables may be large (Table 2).

206

207

Insert Table 1 here

208

209

Insert Table 2 here

210 As identified by Table 3 for anterior hopping direction, hierarchical multiple linear regression
211 identified concentric flexion ($R^2 = 0.266$), and the addition of all contraction types ($R^2 = 0.580$)
212 were large predictors for $TTS Comp_x$. For $Comp_y$, it was identified that concentric flexion and
213 eccentric extension ($R^2 = 0.502$), concentric flexion and concentric extension ($R^2 = 0.502$), and
214 the addition of all contraction types ($R^2 = 0.800$) were large predictors. Moreover, eccentric
215 flexion ($R^2 = 0.310$) and concentric extension ($R^2 = 0.294$), and the addition of all contraction
216 types ($R^2 = 0.548$) were large predictors of CoP_y . All other iterations of hierarchical multiple
217 regression yielded results that were weak predictors for anterior hopping. For the strength ratio
218 data, minimal associations were identified for all anterior hopping-based measures ($R^2 < 0.13$,
219 $P > 0.05$).

220

Insert Table 3 here

221 For medial hops, as identified by Table 4, eccentric flexion and concentric extension ($R^2 =$
222 0.561), and the addition of all contraction types ($R^2 = 0.655$) were large predictors ($P \leq 0.05$)
223 for $TTS Comp_x$. For $TTS Comp_y$, eccentric flexion ($R^2 = 0.267$), the addition of concentric
224 extension ($R^2 = 0.492$), and although reducing the accounted variance, the addition of all
225 contraction types ($R^2 = 0.483$) were also large predictors. For $TTS Comp_z$, eccentric flexion
226 and concentric extension ($R^2 = 0.594$), and the addition of all contraction types ($R^2 = 0.788$)
227 were large predictors. Moreover, all contraction types were large predictors ($R^2 = 0.615$) for
228 CoP_y . All other iterations of hierarchical multiple regression yielded results that were weak
229 predictors for medial hopping. For the strength ratio data, minimal associations were identified
230 for all anterior hopping-based measures ($R^2 < 0.16$, $P > 0.05$), apart from concentric trunk
231 flexion/eccentric trunk extension ratios for $Comp_x$ ($R^2 0.27$; $P = 0.048$), $Comp_y$ ($R^2 0.36$; $P =$
232 0.019) and $Comp_z$ ($R^2 0.29$; $P = 0.037$).

233

234

Insert Table 4 here

235

Table 5 identifies the linear relationship between indices of CoP and *TTS Comp* values using

236

Pearson's correlation. Although CoP_x and $TTS Comp_z$ for anterior hopping and CoP_y and TTS

237

$Comp_x$ for medial hopping were moderate (Cohen 1988), these observations were however

238

not significant ($P > 0.05$).

239

Insert Table 5 here

240

241 Discussion

242

The study aims were to assess if isokinetic peak torques of the concentric and eccentric trunk

243

flexors/extensors were a predictor for CoP_{XY} and TTS_{XYZ} during an anterior and medial hop

244

and hold task in children. The findings identified for anterior hopping that concentric trunk

245

flexor peak torques were the strongest predictor for $TTS Comp_{XY}$. The combination of

246

concentric flexion and eccentric extension peak torques were also strong predictors for TTS

247

$Comp_Y$. For medial hopping, it was identified that eccentric flexion and concentric extension

248

peak torques were strong predictors for $TTS Comp_{XYZ}$, with the combination of all contraction

249

modes strengthened these observations. The present findings may need to be considered

250

with some caution due to evidence of large variation yielded within the data. Nevertheless,

251

these findings reiterate the need to assess trunk musculature strength in children due to the

252

strong link identified with balance and helps to inform the choice of methods used to determine

253

TTS . As such, the current observations may be important to help identify if children possess

254

sufficient trunk musculature strength during the completion of hopping tasks that can also be

255

used to aid the development of motor competence in younger populations. Since the ability to

256

maintain postural control in children is not fully developed, this present study could suggest

257

that the development of trunk musculature strength may have subsequent improvements in

258

dynamic balance tasks. As such, the inclusion of core strengthening exercises in combination

259

with other training modalities aimed to improve motor control in children may also be adopted.

260

261 The present study identified for anterior hop and hold tasks, concentric trunk flexor peak
262 torques were related to increased stabilisation time and postural sway, in accordance with
263 previous observations (Hammami et al. 2016). These observations may be accounted by the
264 landing strategies adopted by the participants during anterior hopping tasks where it can be
265 assumed that the centre of mass is anteriorly displaced relative to the base of support. As
266 such, a concentric trunk flexion during this period of stabilisation would be counterintuitive,
267 increasing TTS and CoP postural sway in young children. Because motor control is not fully
268 developed, this may also account for these differing findings compared to previous studies
269 (Wdowski et al. 2021). These observations are also supported during medial hopping tasks,
270 where strong relationships were associated with increased stabilisation time and sway, and
271 further influenced by the increased complexity of this hopping direction. The muscular
272 activities during the completion of hopping tasks are also likely to play a role during the
273 stabilisation phase of the task. Previous research supports these claims, with observations
274 demonstrating that trunk musculature activity (and co-contraction of the anterior and posterior
275 musculature) in children with cerebral palsy and developmental coordination disorder have a
276 higher EMG magnitude and increased time to activate their trunk when compared to healthy
277 children (Prosser et al. 2010; Kane and Barden, 2011). The findings from the present study
278 also support these previous observations, as concentric flexion and eccentric extension
279 (including the concentric flexion and eccentric extension strength ratios for medial hopping),
280 and eccentric flexion and concentric extension peak torques are associated with decreased
281 $TTS Comp_Y$ and $TTS Comp_{XYZ}$, respectively. As such, it could be suggested the timing and
282 co-contraction of the trunk musculature are also important considerations during the
283 stabilisation phase of dynamics tasks.

284

285 The combination of muscular contractions of the trunk flexors and extensors also requires
286 attention relative to the mechanical demands of balance. In the current study combinations of

287 eccentric flexion and concentric extension trunk strength for anterior and medial hopping tasks
288 accounted for some variation in $TTS\ Comp_{XY}$ and $TTS\ Comp_{XYZ}$, respectively. These findings
289 support previous work in pediatric populations and identified overall/trunk muscular strength
290 influences balance (Ibrahim et al. 2013; Mitchell et al. 2015; Hammami et al. 2016). These
291 aforementioned studies did not entirely isolate the trunk during strength assessments, and did
292 not directly assess postural sway or TTS, limiting comparisons with these observations.
293 Isokinetic strength assessments of the trunk musculature have been previously conducted in
294 young in children and early adolescence to establish the relationship with balance (Müller et
295 al. 2014; Bernard et al. 2014; Barczyk-Pawelec et al. 2015), with these findings also agreeing
296 with present observations. However, previous observations have not included eccentric
297 strength assessments of the trunk musculature in children. The combination of concentric and
298 eccentric actions for the trunk also accounted for variation in CoP_Y for anterior and medial hop
299 tasks. The importance of eccentric trunk actions may be more relevant to the mechanical
300 demands of balance by aiding deceleration and stopping within the base of support. Given
301 that eccentric exercise appears to elicit a greater increase in muscular force production to
302 traditional concentric based exercises (Roig et al. 2009), this may be a viable way to increase
303 trunk musculature strength and may benefit young individuals to develop balance.

304

305 The results of the present study also identified limited relationships between TTS composite
306 scores compared to CoP during hopping tasks. The TTS calculation based on previous
307 observations (Fransz et al. 2015) are influenced by the quiet standing noise during the
308 stabilisation phase. It is possible to have a low TTS that could be achieved by a high quiet
309 standing noise, thereby creating a larger range for stability to be achieved. As such, adjusting
310 the typical TTS to be proportionate to the stabilisation range appears to mitigate this issue,
311 with lower values demonstrating superior $TTS\ Comp$. With limited association with postural
312 sway CoP , these observations could suggest being independent. It could also be interpreted
313 that CoP may be a more robust method to quantify balance since this method consider

314 displacement covered during the task. Nevertheless, using TTS without the considering of the
315 bound ranges influences TTS, which could be misleading.

316

317 It must be acknowledged that this study is not without limitations. As previously identified in
318 the methods section, this study is likely to have insufficient statistical power for all outcome
319 variables as it was not possible to recruit the specified number of participants. As such, the
320 study may be at increased risk of observing a false negative. The present study also did not
321 provide feedback during the experimental trials during the collection of isokinetic trunk strength
322 to standardise feedback cues, but this may result in reduced peak torques, and may be seen
323 as another limitation. There was evidence of large variation of the present data. If future
324 research and/or practitioners wish to assess these current outcomes measures in children
325 using interventions, improvements would need to eclipse the variation of test. It must also be
326 noted that other musculature (such as the lower limbs) are also likely to play a role during
327 stabilisation of hopping tasks, thus future studies may wish to look at the combined effects of
328 trunk and lower extremities contributions. Future investigations may also wish to consider the
329 magnitude and time to peak muscular activity (or relevant phases and/or time durations) during
330 the completion of functional tasks, and during isokinetic trunk strength assessments (Prosser
331 et al. 2010; Kane and Barden, 2011).

332

333 **Conclusion**

334 The present study identified that the combination of concentric trunk flexion and eccentric
335 trunk extension were able to account for a large proportion of *TTS Comp* for hop and hold
336 tasks, and further strengthened when all muscle actions were included. It was also identified
337 that *TTS Comp* demonstrated limited relationships with CoP, meaning these methods may be
338 independent of each other, or provides further justification for CoP. These findings have
339 implications for the assessment of trunk musculature strength and measures of postural

340 control within a young healthy population. To improve trunk musculature strength and the
341 potential to maintain postural control, a combination of concentric and eccentric exercises
342 appears relevant due to the increased relevance to the demands of balance maintenance.
343 Future investigations may also wish to consider the magnitude and time to peak muscular
344 activity (or relevant phases and/or time durations) during the completion of functional tasks,
345 and during isokinetic trunk strength assessments coupled with the lower extremities.

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Table 1. Descriptive Statistics of Balance Metrics in Anterior Hop and Hold and Isokinetic Peak Torques of the Trunk Musculature Isokinetic Strength

Concentric Trunk Flexor Peak Torque (Nm)	Concentric Trunk Extensor Peak Torque (Nm)	Eccentric Trunk Flexor Peak Torque (Nm)	Eccentric Trunk Extensor Peak Torque (Nm)	
Angle of Peak Torque (°)	Angle of Peak Torque (°)	Angle of Peak Torque (°)	Angle of Peak Torque (°)	
58.30 ± 25.94	88.61 ± 36.22	94.81 ± 31.77	131.43 ± 45.05	
17.04 ± 12.24	32.18 ± 7.52	14.43 ± 11.17	29.93 ± 7.34	
Anterior Hop and Hold				
xComp (Au)	yComp (Au)	zComp (Au)	xCoP (m)	yCoP (m)
25.11 ± 17.75	20.76 ± 11.07	43.36 ± 17.55	1.21 ± 1.04	2.95 ± 1.59
Medial Hop and Hold				
xComp (Au)	yComp (Au)	zComp (Au)	xCoP (m)	yCoP (m)
26.23 ± 18.04	34.03 ± 19.86	80.27 ± 86.69	2.38 ± 1.74	1.41 ± 1.14
<i>N=17 in each case</i>				

Table 2. Standard Error of Measurement (SEM) Hop in Balance Metrics of Anterior Hop and Hold and Isokinetic Peak Torques of the Trunk Musculature

	<i>TTS Comp_x</i>	<i>TTS Comp_y</i>	<i>TTS Comp_z</i>	<i>CoP_x</i>	<i>CoP_y</i>
<i>Anterior Hop</i>	7.65au	4.31au	15.45au	0.89m	1.34m
<i>Medial Hop</i>	15.19au	16.04au	69.89au	1.42m	0.92m
	<i>Concentric Peak Torque</i>	<i>Eccentric Peak Torque</i>			
<i>Isokinetic Trunk Flexion</i>	29.55Nm	29.73Nm			
<i>Isokinetic Trunk Extension</i>	28.26Nm	33.14Nm			

N=17 in each case

arbitrary unit (au)

metre(m)

newton metre (Nm)

Table.3 Hierarchal Multiple Linear Regression of Balance Metrics of Anterior Hop and Hold and Isokinetic Peak Torques of the Trunk Musculature

	Model 1 Concentric flexion	Model 2 Concentric extension	Model 3 Eccentric flexion	Model 4 Eccentric extension	Model 5 Concentric flexion + eccentric extension	Model 6 Eccentric flexion + concentric extension	Model 7 Concentric flexion + concentric extension	Model 8 Eccentric flexion + eccentric extension	Model 9 Concentric flexion + concentric extension + eccentric flexion + eccentric extension
TTS Comp_x	R ² = 0.266 P = 0.048	R ² < 0.001 P = 0.770	R ² < 0.001 P = 0.916	R ² < 0.001 P = 0.785	R ² = 0.333 Δ R ² = 0.067; P = 0.087	R ² = 0.007 Δ R ² = 0.006 P = 0.955	R ² = 0.277 Δ R ² = 0.011 P = 0.142	R ² = 0.254 Δ R ² = 0.253 P = 0.856	R ² = 0.580 Δ R ² = 0.303 P < 0.001
TTS Comp_y	R ² = 0.499 P < 0.001	R ² = 0.088; P = 0.281	R ² = 0.071 P = 0.337	R ² = 0.030 P = 0.536	R ² = 0.502 Δ R ² = 0.003 P = 0.015	R ² = 0.099 Δ R ² = 0.011 P = 0.532	R ² = 0.502 Δ R ² = 0.003 P = 0.015	R ² = 0.07 Δ R ² = 0.003 P = 0.632	R ² = 0.800 Δ R ² = 0.298 P < 0.001
TTS Comp_z	R ² = 0.002 P = 0.864	R ² = 0.013 P = 0.679	R ² < 0.001 P = 0.763	R ² = 0.001 P = 0.720	R ² = 0.174 Δ R ² = 0.172 P = 0.899	R ² = 0.050 Δ R ² = 0.037 P = 0.720	R ² = 0.022 Δ R ² = 0.020 P = 0.872	R ² = 0.075 Δ R ² = 0.074 P = 0.625	R ² = 0.007 Δ R ² = -0.015 P = 0.957
CoP_x	R ² = 0.013 P = 0.677	R ² = 0.087 P = 0.284	R ² = 0.026 P = 0.563	R ² = 0.188 P = 0.105	R ² = 0.189 Δ R ² = 0.176 P = 0.283	R ² = 0.088 Δ R ² = 0.001 P = 0.574	R ² = 0.087 Δ R ² = 0.002 P = 0.575	R ² = 0.262 Δ R ² = 0.236 P = 0.160	R ² = 0.137 Δ R ² = - 0.125 P = 0.413
CoP_y	R ² = 0.019 P = 0.616	R ² = 0.310 P = 0.031	R ² = 0.081 P = 0.303	R ² = 0.294 P = 0.036	R ² = 0.295 Δ R ² = 0.276 P = 0.122	R ² = 0.315 Δ R ² = 0.005 P = 0.102	R ² = 0.313 Δ R ² = 0.294 P = 0.105	R ² = 0.337 Δ R ² = 0.256 P = 0.084	R ² = 0.548 Δ R ² = 0.211 P = 0.008

Concentric flexion: model 1, model 5, model 7, model 9; **concentric extension,** model 2, model 6, model 7, model 9; **eccentric flexion:** model 3, model 6, model 8, model 9; **eccentric extension:** model 4, model 5, model 8, model 9.

Table.4 Hierarchal Multiple Linear Regression of Balance Metrics of Medial Hop and Hold and Isokinetic Peak Torques of the Trunk Musculature

	Model 1 Concentric flexion	Model 2 Concentric extension	Model 3 Eccentric flexion	Model 4 Eccentric extension	Model 5 Concentric flexion + eccentric extension	Model 6 Eccentric flexion + concentric extension	Model 7 Concentric flexion + concentric extension	Model 8 Eccentric flexion + eccentric extension	Model 9 Concentric flexion + concentric extension + eccentric flexion + eccentric extension
TTS Comp_x	R ² = 0.032 P = 0.521	R ² = 0.087 P = 0.285	R ² < 0.001 P = 0.916	R ² = 0.018 P = 0.6244	R ² = 0.039 Δ R ² = 0.007 P = 0.785	R ² = 0.561 Δ R ² = 0.474 P = 0.007	R ² = 0.177 Δ R ² = 0.145 P = 0.310	R ² = 0.177 Δ R ² = 0.176 P = 0.309	R ² = 0.655 Δ R ² = 0.478 P = 0.001
TTS Comp_y	R ² = 0.153 P = 0.148	R ² = 0.002 P = 0.847	R ² = 0.267 P = 0.048	R ² = 0.006 P = 0.354	R ² = 0.172 Δ R ² = 0.019 P = 0.320	R ² = 0.492 Δ R ² = 0.490 P = 0.017	R ² = 0.194 Δ R ² = 0.041 P = 0.273	R ² = 0.316 Δ R ² = 0.049 P = 0.101	R ² = 0.483 Δ R ² = -0.009 P = 0.019
TTS Comp_z	R ² = 0.011 P = 0.211	R ² = 0.009 P = 0.264	R ² = 0.133 P = 0.179	R ² = 0.001 P = 0.888	R ² = 0.122 Δ R ² = 0.111 P = 0.455	R ² = 0.594 Δ R ² = 0.585 P < 0.001	R ² = 0.323 Δ R ² = 0.312 P = 0.096	R ² = 0.279 Δ R ² = 0.146 P = 0.140	R ² = 0.788 Δ R ² = 0.526 P < 0.001
CoP_x	R ² = 0.005 P = 0.381	R ² = 0.111 P = 0.223	R ² = 0.119 P = 0.208	R ² = 0.144 P = 0.162	R ² = 0.160 Δ R ² = 0.155 P = 0.350	R ² = 0.142 Δ R ² = 0.031 P = 0.397	R ² = 0.130 Δ R ² = 0.125 P = 0.432	R ² = 0.150 Δ R ² = 0.039 P = 0.374	R ² = 0.243 Δ R ² = - 0.093 P = 0.187

CoP_Y	$R^2 = 0.024$ $P = 0.578$	$R^2 = 0.014$ $P = 0.672$	$R^2 = 0.047$ $P = 0.435$	$R^2 = 0.003$ $P = 0.827$	$R^2 = 0.038$ $\Delta R^2 = 0.014$ $P = 0.790$	$R^2 = 0.151$ $\Delta R^2 = 0.137$ $P = 0.373$	$R^2 = 0.058$ $\Delta R^2 = 0.034$ $P = 0.697$	$R^2 = 0.177$ $\Delta R^2 = 0.130$ $P = 0.309$	$R^2 = 0.615$ $\Delta R^2 = 0.438$ $P < 0.001$
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Concentric flexion: model 1, model 5, model 7, model 9; **concentric extension,** model 2, model 6, model 7, model 9; **eccentric flexion:** model 3, model 6, model 8, model 9; **eccentric extension:** model 4, model 5, model 8, model 9.

**Table 5. Relationships Between Centre of Pressure Co-ordinates and Time to Stability Composite Scores
Anterior Hop and Hold**

	<i>TTS Comp_x</i>	<i>TTS Comp_y</i>	<i>TTS Comp_z</i>
CoP_x	r = -0.111; P = 0.693	r = 0.030; P = 0.916	r = 0.438; P = 0.102
CoP_y	r = -0.180; P = 0.521	r = 0.060; P = 0.832	r = 0.353; P = 0.197

Medial Hop and Hold

	<i>TTS Comp_x</i>	<i>TTS Comp_y</i>	<i>TTS Comp_z</i>
CoP_x	r = 0.297; P = 0.282	r = 0.032; P = 0.909	r = 0.101; P = 0.721
CoP_y	r = 0.504; P = 0.056	r = 0.144; P = 0.608	r = 0.255; P = 0.359

N=17 in each case

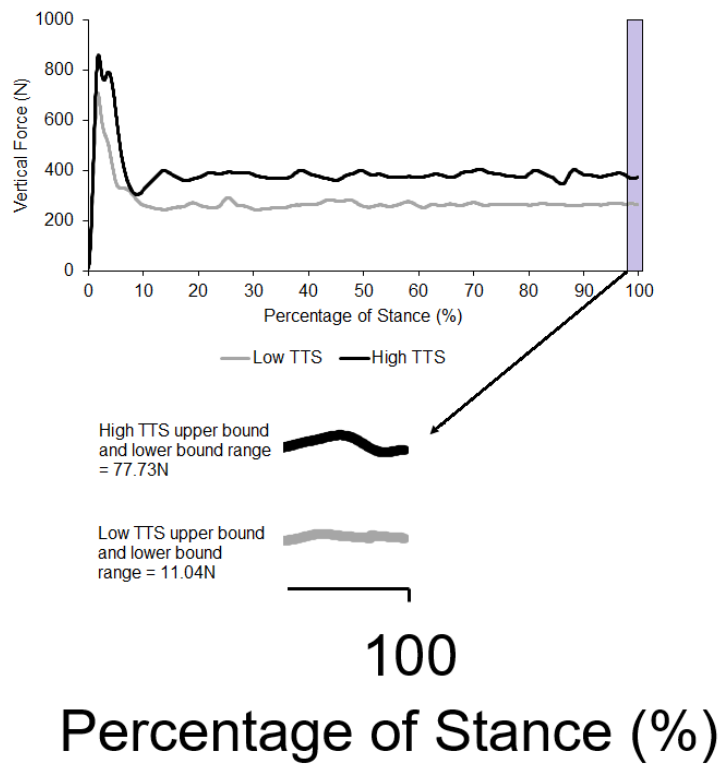


Figure 1. illustrates the influence of increased standing noise/variability and how this may increase the upper and lower bounds used to determine when stabilisation is achieved. Those who are less stable (example one in black) create a larger range, making stability easier to achieve when compared to those who are more stable (example 2 in grey).