A Practical Guide to Analysing the Force-Time Curve of Isometric Tasks in Excel

AUTHORS:

Shyam Chavda – MSc, PGCHE, CSCS, ASCC, CES[1], Anthony N Turner – PhD, CSCS*D[1], Paul Comfort – PhD, CSCS, ASCC[2], G Gregory Haff – PhD[2,3] , Steve Williams – MSc, PGCHE[1], Chris Bishop –MSc, PGCHE, ASCC [1] and Jason P Lake – PhD[4].

INSTITUTION:

1. London Sports Institute, Middlesex University, Allianz Park, Greenlands Lane, NW4 1RL

2. Directorate of Sport, Exercise and Physiotherapy, University of Salford, Salford, Greater Manchester, UK

3. Centre for Exercise and Sports Science Research, Edith Cowan University, Joondalup, Australia.

4. Chichester Institute of Sport, University of Chichester, College Lane, Chichester, PO19 6PE.

CORRESPONDENCE:

Email: s.chavda@mdx.ac.uk

Tel No: (+44)20 8411 2854

Address: As per above

Shyam Chavda is a strength and conditioning coach and technical tutor at the London Sport Institute, Middlesex University. He is also the performance scientist for British Weightlifting and head coach at Middlesex University weightlifting club.

Anthony N Turner is the director of postgraduate programmes in sport at the London Sport Institute, Middlesex University.

Paul Comfort is a reader in Strength and Conditioning and the program leader for the Masters degree in Strength and Conditioning at the University of Salford.

G. Gregory Haff is a Professor of Strength and Conditioning and course coordinator of the MSc in Exercise Science (Strength and Conditioning) at Edith Cowan University. He is also an Honorary Professor in the Directorate of Sport, Exercise and Physiotherapy at the University of Salford.

Steve Williams is a lecturer in biomechanics at the London Sport Institute, Middlesex University.

Chris Bishop is a strength and conditioning coach at the London Sport Institute, Middlesex University, where he is also the programme leader for the MSc in Strength and Conditioning.

Jason Lake is a Reader in Sport and Exercise Biomechanics and program leader of the MSc in Strength and Conditioning in the Chichester Institute of Sport at the University of Chichester

1   **A Practical Guide to Analysing the Force-Time Curve of Isometric Tasks in Excel**

2

3   **Abstract**

4   Understanding force generating capabilities of athletes is an important facet of strength

5   diagnostics. The utilisation of isometric tasks such as the isometric squat and isometric mid-

6   thigh pull are therefore popular methods used to gain a deeper understanding as to what strength

7   characteristics have changed over a given period. This article aims to provide information on

8   how to understand and analyse the force time curve of isometric tasks in Microsoft Excel, thus

9   providing practitioners an inexpensive and accessible alternative to readily available software

10   on the market.

11   Keywords: force;   Rate   of   force   Development;   Isometric   Strength;   excel

12

13

14   **Introduction**

15   Lower-body neuromuscular force production characteristics have previously been determined

16   utilising isometric tasks such as the isometric mid-thigh pull (IMTP) (34, 36, 42-44, 49, 51),

17   isometric squat (IS) (3, 12, 36, 39, 47), isometric leg press (7, 55), and isometric dynamometry

18   (38, 41, 46). Relative to multi-joint isometric assessments, such as the IS and IMTP, isolating

19   a single joint requires specialist equipment such as a dynamometer which in most cases will

20   not be financially viable or practical. Although testing multi-joint isometrics requires a force

21   plate and a specialised isometric rack, a variety of testing systems are available ranging from

22   customised laboratory set ups (Figure 1a), to more portable and affordable set ups (Figure 1b).

23   Previous literature has shown conflicting evidence regarding single joint isometrics and their

24 correlations to dynamic performance (15, 35, 38, 40, 53), suggesting that they do not simulate

25 body positions representative of dynamic tasks such as jumping (2, 54), and do not best

26 represent the transfer of forces through the kinetic chain and are therefore considered a poor

27 indicator of athletic performance (36). Conversely, the IS and IMTP are used more frequently

28 (12, 23, 26, 28, 36, 47, 49, 51), potentially due to affordability (relative to a dynamometer), set

29 up efficiency, and greater replication of multi-joint positions demonstrated within sporting

30 actions. Although inconsistencies in methodologies and analysis of the force time curve is

31 evident among the literature (14), variables assessed during multi-joint isometric assessments

32 still demonstrate stronger relationships to dynamic tasks in comparison to single-joint isometric

33 assessments (23, 24, 33, 34, 45, 47, 52), with less conflicting evidence reported (36). Therefore,

34 it is unsurprising that multi-joint isometric tests such as the IS and IMTP are a more popular

35 choice amongst practitioners and will therefore be the focus of this article.

36

37 **INSERT FIGURE 1a and b HERE NEXT TO EACHOTHER – LAB (a) and PORTABLE

38 (b) ISO RIG**

39

40 The IS and IMTP data have been measured using crane scales (50), single -axial load cells (28)

41 and more commonly force plates, that are positioned underneath a fixed bar or within a custom

42 testing rack (Figure 1 a and b). The effort an athlete applies to the bar by pushing (IS) or pulling

43 (IMTP) against it is transmitted through the ground and the vertical ground reaction force

44 (vGRF) is recorded. Important methodological factors that can influence the quality of this

45 vGRF data are set up and sampling frequency (5, 14, 19, 31). Additionally, subsequent analysis

46 of the force-time data can be affected by the way in which the start of the pull / push is

47 determined (17). Since not all institution or teams have access to software that can

48 automatically provide variables of interest, the aim of this article is to provide readers with

49 methodological guidelines for IS and IMTP data collection and a practical guide on how to

50 develop a spreadsheet to analyse the force-time curve to obtain appropriate variables of interest.

51

Variables for Consideration

Peak Force

54 Typically, the IS and IMTP are used to identify an athlete's ability to generate maximal force

55 during a given task, this is termed peak force (PF). This variable has been shown to be produced

56 at between 200 and 400 ms of test performance (23, 29) and represents the largest value on the

57 force-time curve (Figure 2). Researchers have found strong relationships between PF and

58 dynamic tasks, such as one repetition maximum (1RM) back squats (r = 0.79 - 0.97) (3, 34,

59 51), weightlifting performance (r = 0.80) (4, 26), vertical jump height (r = 0.72 – 0.95) (29, 34,

60 49), change of direction (r = -0.657) and sprint (5, 10, 15 and 20 meters) performance (r = -

61 0.62 - 0.69) (49). It has been posited that this is because the ability to generate large maximal

62 forces (both absolute and relative) underpins one's capacity to accelerate sports-related mass,

63 typically referring to the athlete during jumping, sprinting, and changing direction (45, 47, 52).

64 Since PF is a highly reliable variable in both IMTP (CV = 1.7% -3.7%, ICC = 0.97- 0.99) (16,

65 18, 26) and IS (CV = 0.9%, ICC = 0.97) (6), and strongly related to performance, this would

66 suggest that the ability to produce high forces is desirable for athletic performance. However,

67 to provide practitioners with valuable information that isoinertial tests cannot, insights into

68 what specific strength quality has improved to contribute to a specific outcome (e.g. jumping

69 higher or throwing an implement further) (3) would typically be related to time. Since, the

70 execution of dynamic athletic tasks such as jumping are generally constrained by time (i.e. the

71 athlete cannot afford to execute the task over more time or would need to reduce the time of

72 execution), PF alone may not provide enough information about the adaptation of strength

73 qualities. This may be why force at specific time points and the rate of force development

74 (RFD) (12, 34, 38, 39, 42- 44, 46, 47, 49, 51) are useful to include into IS and IMTP force-time

75 data analysis to help maximise insight into an athlete's performance capacity.

76

77 **INSERT FIGURE 2 HERE – FTC IMAGE**

78

79 ***Time related force values***

80 Force at specific time points is another metric often reported in the literature (17, 18, 28, 51).

81 This metric simply reports the force value at a given time point and can provide insight about

82 the change in force at time points of interest following training interventions. That is to say that

83 if an athlete is able to produce 800 N of force at 100 ms one would hope for an upward shift

84 following a training intervention focused on speed and power so that they may then achieve

85 950 N at the same time point. Time related force values have demonstrated good reliability

86 (CV = 2.3%-2.7% and 6.2-8.0%, ICC = 0.95-1.00 and 0.921-0.968) (18, 26). Force at 0 -90, -

87 100, -150, -200 and -250 ms have also been shown to have moderate to strong correlations with

88 back squat 1RM (r = 0.757-0.816), (28), CMJ height (r = 0.346), RSImod (r = 0.416-0.426)

89 and 1 RM power clean performance (r = 0.569-0.659) (18). Given its relationship to athletic

90 tasks, and its reliability, force at specific time points may provide a useful insight into the

91 athlete's physical capacity. Following an intervention an increase in this value at given time

92 point (i.e 200 ms) would infer that RFD and impulse (discussed below) would have also

93 increased relative to the onset (i.e baseline) (Figure 2). Since the calculation of RFD amplifies

94 signal noise using force at specific time points would introduce less error and simplify data

95 analysis.

96

97 ***RFD***

98 RFD describes the gradient (steepness) of the force-time curve and is underpinned by

99 differentiation of force. This is achieved by dividing the change in force (ΔF [where Δ =

100 change]) by the change in time (Δt) (26). The RFD is typically calculated across specific epochs

101 associated with athletic movements as shown in Figure 2. Average RFD (aRFD) is calculated

102 by dividing PF by time to PF. However, this metric has low reliability (CV <15%, ICC = 0.74)

103 (26), potentially due to PF being achieved at different time points between trials, day and

104 individuals. Therefore, to address this and to provide practitioners with a clearer picture of

105 force generating capabilities during times relevant to sporting tasks, utilising pre-determined

106 epochs is a preferred method of analysis (12, 16-19, 26, 28, 47, 51). RFD can be calculated

107 from the initiation of the start of the task (0 ms) to a specific time point (e.g., 0-100 ms) of

108 which the force at 100 ms is then divided by 0.100 (100 ms) (1). In order to define the steepest

109 part of the curve researchers have also utilised peak RFD (pRFD) where epochs of equal length

110 sequentially measure RFD using consecutive time periods up the slope (i.e, 50-100, 100-150

111 ms, etc). Haff et al (26) demonstrated that pRFD is reliable when a 20 ms moving average was

112 used as opposed to 50, 30, 10, 5 and 2 ms, all of which displayed CV's greater than 15% and

113 low ICC's.

114

115 The relationship between measures of RFD and athletic performance have previously

116 demonstrated moderate to strong relationships (3, 49) in tasks such as hang clean 1RM (*r* =

117 0.668- 0.701), vertical jump height (r = 0.556-0.570) and 1RM squat, both full and partial (r =

118 0.423-0.554), with small and non-significant relationships also having been reported within

119 front squat 1RM (r = 0.119 − 0.466), pro and lane agility (r = -0.179- -0.378) and

120 countermovement and squat jump (CMJ and SJ, respectively) height (r = -0.04 − 0.13), (34,

121 44, 49). This disparity may be attributed to a multitude of factors such as; small epochs being

122 too sensitive and therefore unreliable (31), different onset thresholds and different sampling

123 frequencies utilised in the research. Dos'Santos et al. (16) concluded that to obtain reliable

124 RFD and time-specific force values data could be sampled as low as 500 Hz, however, in order

125 to capture all relevant signals, the authors suggest a capture frequency of 1,000 Hz. Also due

126 to inherent noise experienced from the force plate an onset threshold of pre-pull quiet standing

127 mean + 5 standard deviations (5SD) sufficiently accounts for both signal and human 'noise'

128 (17). However, in fixed laboratory set ups (figure 1a) noise may likely be less and therefore a

129 lower standard deviation may suffice. Since using either an automated method (e.g. + 5

130 standard deviations) or manual inspection to determine the onset will have an impact on time-

131 related force variables more research is needed to determine the best onset method based on

132 the set-up in which the data is being collected.

133

134 Early phase RFD (<50 ms) may be unreliable due to electro-mechanical delay (EMD). This is

135 the time between the onset of muscle activity and the onset of mechanical output. This is best

136 described by Folland et al (21) who utilised a dynamometer to measure a series of voluntary

137 and electrically evoked isometric contractions of the quadriceps. Their findings reported high

138 interindividual variability (CV = 48%) in RFD during 0-50 ms during isometric knee extension,

139 with electrically evoked contractions showing over half this variability in the twitch (CV =

140 22%) and octet (eight pulses at 300 Hz) (CV = 19%) conditions. They conclude that this

141 variability is caused by neural factors, supported by the high interindividual variability (CV =

142 38%) presented in the activation of the quadriceps, as identified through electromyography

143 (EMG). Since EMD is <13 ms for voluntary contractions (48), the advised sampling frequency

144 of 1,000 Hz by the authors makes it less likely to miss any signal relevant to the isometric task.

145 It should also be noted that as a virtue of differentiating the force-time data signal noise is

146 amplified, therefore potentially accounting for the variability often reported in RFD measures.

147

Impulse

149 Impulse (area under the curve) is of high importance in sporting tasks since it explains the

150 change in momentum (mass × velocity) as a consequence of the product of net force (force less

151 body [and additional external] weight) and how long it is applied for. During isometric tasks,

152 impulse can be calculated using the same approach as that mentioned for RFD, multiplying

153 instead of dividing force by time:

154 $\underline{F}\Delta t = m\Delta v$

155 Where F is force, t is time, m is mass, and v is velocity. Since velocity is 0 throughout isometric

156 tasks and should therefore not be presented, the amount of force an athlete can apply and the

157 time over which they can apply it, can provide insight into the athlete's velocity capacity to

158 enable change in their momentum during non-isometric athletic tasks. Therefore, at a constant

159 body mass, a greater impulse at a given epoch would suggest an increase in the athlete's

160 capacity to generate greater movement velocity. Since impulse can be achieved through a

161 variation of high force and less time as well as low force and more time, it is important to

162 understand that during sporting tasks the athlete will rely on the amount of force they can apply

163 with respect to the time they have to apply it. For example, during top end sprinting it is

164 undesirable for the athlete to generate greater vertical impulse through longer ground contact,

165 applying more force in the typically shorter available time is desirable. In lesser time

166 constrained movements, such as throwing an implement (i.e., a shot putt), the athlete who

167 applies the greatest net force over a longer time period would be able to throw the implement

168 further since they have a longer time to apply force to the shot. Relationships between impulse

169 and non-time constrained athletic tasks have been found to have moderate correlations. For

170 example, IS impulse at 250 ms, and at 90-120 degrees knee flexion, both displayed strong to

171 moderate correlation with 1RM squat ($r = 0.7, 0.58$) (3). This is unsurprising because back

172 squat 1RM movement velocity is low (due to the inverse load-velocity relationship). This

173 means that the athlete is therefore required to produce the necessary force over any time period

174 to complete rep (bar and body mass displacement).

175

176 Literature on impulse collected from isolated joint isometrics have reported similar CV and

177 ICC values to that of RFD, with early phase force production (0- 50 ms) shown to be the most

178 variable (CV = 16.6% and 18.7%, ICC= 0.80 and 0.77), although this improves at 0-100 ms

179 (CV= 6.8% and 9.8%, ICC= 0.90 and 0.82) and 100-150 ms (CV= 10.5% and 8.4% , ICC=

180 0.62 and 0.77) for RFD and impulse respectively (10). Guppy et al (22) had also reported that

181 during IMTP, measures of impulse across a range of epochs were more reliable (CV = 4.3 −

182 8.70%, ICC = 0.89 − 0.97) than RFD when assessing different hip and knee angles. It should

183 therefore be noted that as a virtue of differentiating the force-time curve RFD can be more

184 susceptible to increased error and is magnified when using smaller epochs (31). Therefore, the

185 reader may wish to check the reliability of RFD and impulse within their population to help

186 determine which is more reliable, noting that impulse is indicative of sporting actions.

Test Set Up

187

188 **Isometric Mid-Thigh Pull**

189 For users to collect PF, RFD and impulse, the correct set up of the IMTP and IS must be

190 considered to ensure testing consistency. The IMTP is a position with high similarities to that

191 of the power position in the clean, whereby the largest vGRF is produced when the torso is in

192 an upright position (20, 23, 26). There has been a variety of set up methods used in the literature

193 for the IMTP ranging from a set position at the mid-point of the knee and hip joint (14, 51),

194 and individualised knee and hip angles based on the clean power position (start of the second

195 pull) (22, 23, 26, 29, 36, 43). Research from Comfort et al (13) compared varying hip and knee

196 angles commonly used in previous research (125° and 145°, and 120°,130°,140° and 150°,

197 respectively) to a self-selected position, where the bar was situated at the mid-thigh. They

198 reported that there were no significant differences between kinetic variables at the differing

199 angles for 100, 200and 300 ms, but it is worth noting that the self-selected posture, based on

200 the start of the second pull, resulted in joint angles in line with Haff et al (23-25). Within- and

201 between-session reliability was also reported to be highly reliable for all kinetic measures (ICC

202 = 0.849 – 0.993), with impulse at 130° knee flexion and 125° hip flexion the least reliable at

203 all time points (ICC = 0.731-0.739). This may suggest that the hip and knee angle can be self-

204 selected if the athlete is instructed to adopt the posture required for the start of the second pull,

205 and then recorded for reproducibility by the tester. More recent research from Dos' Santos and

206 colleagues (19) investigated the effects of hip angle on PF and RFD. They concluded that to

207 optimise kinetic output and reduce pre-tension during the weighing period (period prior to

208 onset) a hip and knee angle of 145° should be adopted. This is further supported by the findings

209 of Guppy et al (22) who presented greater means across PF, force at specific time points and

210 impulse at specific epochs during traditional IMTP set up (145° at knee and hip) compared to

211 3 alternative positions (145° and 120°, 120° and 125° and 120° and 145° for the knee and hip

212 angles, respectively.). They also reported low to moderate CV's (4 – 11.1%) and high ICC's

213 (0.86 – 0.98) suggesting that utilising a knee and hip position of ~145° may not only optimise

214   kinetic performance, but also provide highly reliable data. Standardising a knee and hip angle

215   utilising a goniometer is best practice because it enables reproducibility of the test within the

216   same individual, which is critical if utilising the IMTP for monitoring purposes. The angle

217   ranges at the knee and hip are presented in Figure 3, and are typical of that previously presented

218   in the literature (14, 22, 23, 26, 29, 36, 43).

219

220   **INSERT FIGURE 3 HERE – IMTP POSITION IMAGE**

221

222   It should also be noted that to enable the athlete to generate maximum force during the IMTP

223   prior research suggests utilising weightlifting straps and where possible athletic tape to strap

224   the hands of the athlete to the bar to prevent the grip being compromised, which may limit the

225   force output (23, 26, 29).

226

Isometric Squat

227

228   Different knee and hip angles have been used for the isometric squat, ranging from 90 - 140°

229   of knee flexion and 110 - 140° of hip flexion (9). Research from Marchetti et al. (32) has shown

230   that 90° of knee flexion produces the highest overall muscle activation in the quadriceps,

231   hamstrings, and glutes when compared to 20° and 140°. The limitation of this study, however,

232   was that they only compared muscle activity and not ground reaction force. Therefore, it would

233   be unjust to assume that a higher muscle activity at 90° would produce higher vGRF as the

234   heightened muscle activity may also be due to stabilisation at such depth. Since the IMTP

235   replicates the power position of the clean during which the greatest amounts of force (relative

236   to other positions) have been shown to be produced, it would seem logical to utilise a knee

237 angle ~140° for the IS (Figure 4). This has been examined by Brady et al (8) who compared

238 the reliability of specific kinetic variables during IMTP and IS using the same knee and hip

239 angle (knee angle $136 \pm 3°$ and hip angle $137 \pm 2°$). Their results suggested that absolute peak

240 force, relative peak force, allometrically scaled peak force, RFD at $0 - 200$ and 250 ms and

241 impulse between $0 - 300$ ms were deemed reliable (CV < 10%, ICC >0.8).

242

243 **INSERT FIGURE 4 HERE – IS POSITION IMAGE **

244

245 It is important that when athletes set up for these tasks that they take a low-level of pre-tension

246 (48), conversely the athlete should not take so much tension that they are actively pushing or

247 pulling against the bar. Since all of the of force acquisition software that the authors are aware

248 of display force-time data as it is recorded and/or at trial completion, the authors suggest that

249 the reader visually inspect the force-time curve and discard any readings that do not appear to

250 have a flat baseline or display an obvious countermovement before force application (Figure 5

251 a and b, respectively). Alternatively, the reader could use a more robust post analysis method

252 of inclusion and exclusion criteria of trials which is later discussed in the *"Exclusion of Trials"*

253 section. Trials with clear countermovement's should not be used because this will lead to

254 difficulties in determining trial initiation thus compromising the accuracy of time related data.

255 This issue can be avoided by providing clear and concise verbal instruction, instructing the

256 athlete to "get into position" and to "focus on pushing the ground as hard and as fast as

257 possible" (27). Providing these kinds of instructions has been shown to produce significantly

258 greater peak force ($p < 0.001$, ES = 0.33, CI 95%) than internal focus of attention (27).

259

260 **INSERT FIGURE 5a and b HERE ONTOP OF EACHOTHER – FORCE TRACE

261 EXAMPLE **

262

263 An important factor to consider with the IMTP and IS that is often overlooked is the type of

264 rig (where rig refers to the way the bar is positioned) and bar that is used. Where possible, users

265 are recommended to use a purpose-built isometric rig with minimal to no movement and a cold

266 rolled steel bar. This is to minimise the amount of force lost via bar flexion or rig movement.

267 Not doing this may potentially provide misleading outputs, particularly with respect to RFD

268 and other time related variables. It becomes clear that obtaining force-time data during

269 isometric tasks requires a consistent and reliable method to be used from test set-up to data

270 extraction (14) (refer to instruction table below). Since there is such a large discrepancy in the

271 research on position and reliability, the authors suggest readers use table 1 as a guideline to

272 best fit their practice and to then test the reliability of the chosen isometric task within their

273 own settings.

274

275 **INSERT TABLE 1 HERE – INSTRUCTIONS TO COLLECT IS AND IMTP DATA **

276

277   **Analyzing Data**

278 ***Template Set-up***

279 Firstly, a template should be created so that the raw data can be copied into and the variables

280 of interest calculated. All equations presented in appendix 1 to 3 will relate to the row and

281 column numbers presented in Figure 6, however, readers can adjust the layout as they see fit.

282

**INSERT FIGURE 6 HERE – DATA TEMPLATE IMAGE **

284

Baseline Measure

In order to best collect a quiet baseline, the authors suggest calibration of the force plate without the athlete on it. This will zero the force plate and lessen the likelihood of noise from perturbations generated by the athlete. Secondly, since not all acquisition software's will give a live reading it is pivotal that the athlete is strapped to the bar and is in position in order to obtain a good, stable baseline in which the 5SD is calculated. From this point the acquisition of data can begin and the baseline would likely be very low if 1) they are familiar with the test and 2) have stayed still once in position. Once the data has been reliably collected and the data extracted, the raw force-time data can be pasted into cells A2 and B2. This is important so that subsequent variables can be calculated in column C, labelled "Net Force (N)". If key variables are then derived from the raw force-time data athletes with greater mass will be favoured. Unlike other common athletic tasks collected on a force plate (i.e., countermovement jump), there is no period where body weight can be calculated from the force-time data. The tension taken on the bar will create a vertical force in addition to the athlete's bodyweight. Therefore, an average period of approximately 1-2 s should be calculated from the flattest part of the force-time data before initiation (Figure 5a) (equation b, appendix 1). This now needs to be subtracted from the absolute force in column B, to provide net force in column C.

302

Defining the start

304	There has been a considerable lack of consistency with the way that the start of isometric tasks

305	has been identified in force-time, with previous literature utilising absolute values (28) and

306	manual detection (45). More recently a comparison of reliability on PF and RFD measures

307	between manual and algorithm-based detection was conducted by Carroll et al. (11). Results

308	showed near perfect reliability for both methods, but manual detection yielded greater CV's

309	for RFD measures, both within (CV = 16.25 - 20.59%) and between testers (CV = 32.27 –

310	42.17%) with greater reliability prevalent in the larger epochs (200ms vs 50ms). Thus, proving

311	problematic when using manual based analysis for detection of significant change. Carroll et

312	al. (11) concluded that utilising an automated start point for isometric testing may provide

313	superior between tester reliability when compared to manual suggesting that different

314	examiners can be used when collecting data, thus potentially saving time and resources.

315	However, it should be noted that the automated start points presented by Carroll et al (11) is

316	not defined within the paper and that further research is needed to determine if this method is

317	more reliable than other methods of detection. With this in mind the authors suggest utilising

318	a five-standard deviation threshold relative to the baseline noise (i.e., when the athlete has taken

319	pre- tension), for multiple reasons, 1) it accounts for any noise or perturbations in force during

320	the quiet standing period, 2) it provides greater certainty that the onset of contraction identifies

321	a true change in force (16), and 3) it requires less time than manually analysing data which may

322	not be conducive to the reader's work flow. Before defining this point, it is suggested that the

323	reader creates a "scatter with smooth lines" graph of the absolute data to determine where a

324	quiet period exists before the initiation of force application. This would be represented by a

325	relatively constant force for a period of no less than one second. From this the reader can hover

326	the cursor over the graph and obtain row values relating to a "Baseline Start" and "Baseline

327	End" and insert these values in cells G4 and G5 respectively.

328   Now the baseline is determined the starting threshold can be determined using equations c to e

329   (appendix 1). This will calculate and present the average force and 5 SD from this period,

330   summing them to provide the start threshold. This method accounts for both signal and human

331   noise and provides more certainty that the onset of contraction identifies a true change in force,

332   as previously explained. However, some fixed isometric racks may experience less noise,

333   therefore a smaller SD may be used at the user's discretion. Using the MATCH and INDEX

334   functions, the location (row) of this value can be found with its associated time point (equation

335   f and g, respectively. Appendix 1).

336

Exclusion of Trials

338   During the collection of isometric force-time data practitioners need to consider reducing

339   between trial variation by utilising exclusion criteria. Previous research (30) has utilised a PF

340   difference between trials of 250 N, of which a third trial would be taken should that value be

341   exceeded. This ensures the intent of the individual during the test remains consistent and can

342   also be an indication on whether they have warmed up sufficiently.

343   Since baseline + 5SD is determined as a meaningful change in force (16) for the onset of the

344   isometric task, the authors suggest that using a baseline − 5SD may provide an appropriate

345   method of determining whether a countermovement prior to the initiation of the pull is

346   meaningful enough to discard. Previously methods utilising arbitrary values (16) and manual

347   inspection (46) have been used to discard force-time curves displaying countermovement's.

348   Since there is no agreed method for the exclusion of trials, the authors rational is based on

349   previous literature by Owens et al (37) who looked at the onset of movement during a CMJ.

350   Owens suggested that when vGRF minus BW changed ± 5 SD, meaningful movement had

351   occurred that falls outside of the "noise" of the baseline. Although he went on further to suggest

352 that the initiation of the jump should in fact be taken − 30 ms from this identified point to ensure

353 velocity is zero, during an isometric task velocity should not to be considered. Therefore, as a

354 virtue of + 5 SD being meaningful change to determine the onset, - 5SD could be used to

355 determine a meaningful countermovement.

356 The − 5 SD exclusion method can be integrated easily into the sheet to show the user whether

357 the trial is to be kept or discarded. In column I10 to I14 insert the headings as outlined in figure

358 6. Insert the relevant calculations in J10- J14, this will 1) calculate the baseline − 5 SD (equation

359 h, appendix 2) and 2) look for the lowest value (equation I, appendix 2) between the end of the

360 baseline (user defined) and the start of the task (equation j and k, appendix 2). From this an IFS

361 function can be utilised to tell the user whether the minimum value (i.e. the countermovement)

362 is lower than that of the bassline − 5SD (equation l, appendix 2).

363 Alternatively, those with software's displaying live force-time curves, a threshold baseline of

364 10% bodyweight can be used to ensure that the athlete is holding a stable position without too

365 much pretension or unloading, therefore potentially pertaining to a better onset, however,

366 further research is needed as to define an acceptable baseline.

367

368 ***Calculations***

369   ***Peak Force***

370 Because peak force is the greatest value achieved by the athlete during the task, the MAX

371 function can be used to find this value from the "Net Force (N)" data range (equation m,

372 appendix 3). Once found, the row it occurs at can be located using a MATCH function

373 (equation n, appendix 3), this can then be converted to a time in seconds by using the INDEX

374 function (equation o, appendix 3). Finally, the time between the onset and peak force (time to

375 peak force) can also be calculated using equations p (Appendix 3).

376

RFD and force at specific time points

378 Average RFD is the first RFD value that can be calculated by dividing the peak force by the

379 time to peak force (equation q, appendix 3) although this has found to be unreliable (26). To

380 calculate RFD from the onset to pre-determined time points, the reader first needs to determine

381 what time points they are interested in. For this example, we use 100 ms, but once the reader

382 understands how this is done the same methods can be applied to any time interval. In the RFD

383 cell (G23) type in the time frame of interest in seconds (i.e. 100ms is 0.1s). From here 100 ms

384 can be located relative to the onset (equation r, appendix 3), thus allowing the use of a MATCH

385 function to define the cell number (equation s, appendix 3). This can be used to then determine

386 force occurring at 100ms (equation t, appendix 3), which when subtracted from the onset force

387 and divided by the time point of interest, will provide RFD (equation u, appendix 3). For all

388 other time points of interest, readers can repeat this process, alternatively, the time point of

389 interest (cell G23) can be changed, which in turn will change the corresponding RFD values.

390 Peak RFD provides information on the steepest part of the curve using consecutive epochs up

391 the force-time curve (e.g. 100ms to 200ms). To calculate this variable, two-time points must

392 first be defined. If the reader has already set up pre-determined time points for RFD (and force

393 at specific time points) as discussed above, then extraction of peak RFD is simplified. For the

394 epochs of interest simply insert equation v (Appendix 3), where "Fz of above (N)" for each

395 time point is taken away from each other (e.g. Fz of above at 100 ms – Fz of above at 200 ms),

396 divided by the time interval of interest (e.g. 100 ms).

397 ***Impulse***

398 Impulse can be calculated from any period of interest (e.g. 0 – 100 ms or 100-200 ms). To do

399 this, force specified at a specific time point can be multiplied by the time point of interest.

400 Alternatively, the trapezoidal rule of calculating the area under the curve can be added within

401 the epoch of interest. In order to achieve this column D must be set up using equation w

402 (Appendix 3) which in turn will calculate impulse for each time point. Then an INDEX function

403 can be used to sum the impulse between two-time points (equation x and y, appendix 3) which

404 were already defined during the RFD calculation, this can be repeated for any other time period.

405

406 **Graphical Representations**

407 Graphical representation of the isometric task can be useful for the reader to plot time points

408 of interest on to the force-time curve, which in turn can help athletes and coaches contextualise

409 the meaning of some of the variables. To do this, first select column C "Fz-BW (N)" and create

410 a "Scatter with smooth lines". Points of interest, such as peak force and time related variables

411 (e.g. RFD, impulse) can be highlighted within the force-time data by right clicking on the

412 graph, selecting "Select data", "Add" and adding in the name of the point of interest (e.g. peak

413 force) followed by the cell it is situated in under "Series X values" followed by the value in the

414 "Series Y values". To make this visible within the force-time curve, right click and select

415 "Change chart type", where the point of interest "chart type" can be changed to scatter. This

416 will need to be completed for all points of interest should users want them to be define on the

417 force-time curve and when complete will look similar to that depicted in Figure 7.

418

419 **INSERT FIGURE 7 HERE – POI IMAGE**

420

421 **Summary**

422 When collecting IS or IMTP vGRF data it is clear that there are common variables of interest

423 as reported within the research (3, 17, 18, 26, 28, 34, 51). These include peak force, RFD (and

424 their associated measures), force at specific time points, and impulse. Generally, it is agreed

425 that a majority of the variables are reliable, with the exception of average RFD. The reliability

426 of RFD and their associated measures needs to be approached with caution since there is a large

427 disparity within the literature which suggests that earlier time points may not be reliable. The

428 efficacy of these variables will also be dependent on the onset threshold used, the sampling

429 frequency and the position the isometric task is conducted, as well as the type. The authors

430 suggest that the reader tests the reliability and sensitivity of extrapolated variables within their

431 own working environment and can do so by collecting multiple trials and checking the

432 variables CV. Utilising a consistent methodology and the suggestions presented in this article

433 will help readers ensure they are obtaining the best possible information within their practice.

434

435 **Figure 1.** Laboratory fixed isometric rack set up (a) and portable isometric rack set up (b).

436 **Figure 2.** Force Time curve highlighting typical variables of interest.

437 **Figure 3.** Isometric Mid-Thigh (IMTP) Pull Set up and force applied by the subject (red

438 arrows) and the corresponding vGRF (green arrows).

439 **Figure 4.** Isometric Squat (IS) set up and force applied by the subject (red arrows) and the

440 corresponding vGRF (green arrows)

441 **Figure 5.** Example of a raw force time curve displaying a steady baseline (a) and a baseline

442 with a countermovement (b), with force on the x axis and cell number on the y axis. Each trial

443 met a peak force of 1826 and 2023 N, respectively. In this instance both trials fall within the

444 250 N exclusion range.

445 **Figure 6.** Data extrapolation template.

446 **Figure 7**. Line graph depicting the points of interest as calculated within the spreadsheet.

447

448

449 **INSERT APPENDIX TABLES 1-3 AT END**

450 **References**

451 1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Increased

452   rate of force development and neural drive of human skeletal muscle following

453   resistance training. *J Appl Physiol* 93: 1318-1326, 2002.

454

455 2. Baker D, Wilson G, and Carlyon B. Generality versus specificity: A comparison of

456   dynamic and isometric measures of strength and speed-strength. *Eur J Appl Physiol*

457   *Occup Physiol* 68: 350-355, 1994.

458

459 3. Bazyler CD, Beckham GK, and Sato K. The use of the isometric squat as a measure of

460   strength and explosiveness. *J Strength Cond Res* 29: 1386-1392, 2015.

461

4. Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *J Sports Med Phys Fitness* 53: 573-581, 2013.

5. Beckham GK, Sato K, Mizuguchi S, Haff GG, and Stone MH. Effect of body position on force production during the isometric mid-thigh pull. *J Strength Cond Res.* 32: 48-56: 2018.

6. Blazevich AJ, Gill N, and Newton RU. Reliability and validity of two isometric squat tests. *J Strength Cond Res* 16: 298-304, 2002.

7. Bogdanis GC, Tsoukos A, Kaloheri O, Terzis G, Veligekas P, and Brown LE. Comparison between Unilateral and Bilateral Plyometric Training on Single and Double Leg Jumping Performance and Strength. *J Strength Cond Res* 33: 633-640, 2019.

8. Brady CJ, Harrison AJ, Flanagan EP, Haff GG, and Comyns TM. A comparison of the isometric mid-thigh pull and isometric squat: intraday reliability, usefulness and the magnitude of difference between tests. *Int J Sports Physiol Perform* 28: 1-25, 2017.

9. Brady CJ, Harrison AJ, Comyns TM. A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. *Sports Biomech* 21: 1-25, 2018.

486   10. Buckthorpe MW, Hannah R, Pain MTG, Folland JP. Reliability of neuromuscular

487   measurements during explosive isometric contractions, with special reference to

488   electromyography normalisation techniques. *Muscle and Nerve* 46: 566-576, 2012.

489

490   11. Carroll KM, Wagle JP, Sato K, DeWeese BH, Mizuguchi S, and Stone MH. Reliability

491   of a commercially available and algorithm-based kinetic analysis software compared to

492   manual-based software. *Sports Biomech* 18:1-9, 2019.

493

494   12. Comfort P, Graham-Smith P, Matthews MJ, and Bamber C. Strength and power

495   characteristics in English elite rugby league players. *J Strength Cond Res* 25: 1374-

496   1384, 2011.

497

498   13. Comfort P, Jones PA, McMahon JJ, and Newton R. Effect of knee and trunk angle on

499   kinetic variables during the isometric midthigh pull: Test-retest reliability. *Int J Sports*

500   *Physiol Perform* 10: 58-63, 2015.

501

502   14. Comfort P, Dos'Santos T, Beckham G K, Stone M H, Guppy S N, and Haff GG.

503   Standardisation and methodological considerations for the isometric mid-thigh pull.

504   *Strength Cond J*, 2018. [e-pub ahead of print].

505

506   15. De Ruiter CJ, Van Leeuwen D, Heijblom A, Bobbert MF, and De Haan A. Fast

507   unilateral isometric knee extension torque development and bilateral jump height. *Med*

508   *Sci Sports Exerc* 38: 1843-1852, 2006.

509

510   16. Dos'Santos T, Jones, P A, Kelly J, McMahon J J, Comfort P, and Thomas C. Effect of

511   sampling frequency on isometric midthigh-pull kinetics. *Int J Sports Physiol Perform*

512   11: 255-260, 2016.

513

514   17. Dos'Santos T, Jones, P A, Comfort P, and Thomas C. Effect of Different Onset

515   Thresholds on Isometric Mid-Thigh Pull Force-Time Variables. *J Strength Cond Res*

516   31: 3463-3473, 2017a.

517

518

519   18. Dos'Santos T, Thomas C, Comfort P, McMahon J J, and Jones, P A. Relationship

520   between isometric force-time characteristics and dynamic performance. *Sports* 5: 1 -

521   12, 2017b.

522

523   19. Dos'Santos T, Thomas C, Jones, P A, McMahon J J, and Comfort P. The effect of hip

524   joint angle on isometric mid-thigh pull kinetics. *J Strength Cond Res* 31: 2748-2757,

525   2017c.

526

527   20. Enoka RM. The pull in Olympic weightlifting. *Med Sci Sports* 11: 131-137, 1979.

528

529   21. Folland JP, Buckthorpe MW, and Hannah R. Human capacity for explosive force

530   production: Neural and contractile determinants. *Scand J Med Sci Sports* 24: 894-906,

531   2014.

532

533   22. Guppy SN, Brady CJ, Kotani Y, Stone MH, Medic N, and Haff GG. The effect of

534   altering body posture and barbell position on the between-session reliability of force-

535   time curve characteristics in the isometric mid-thigh pull. *Sports* 6: 162-177, 2018.

536

537   23. Haff GG, Stone MH, O'Bryant HS, Harman E, Dinan C, Johnson R, and Han K-H.

538   Force-time dependent characteristics of dynamic and isometric muscle actions. *J*

539   *Strength Cond Res* 11: 269-272, 1997.

540

541   24. Haff GG, Carlock JM, Hartman MJ, Kilgore JL, Kawamori N, Jackson JR, Morris RT,

542   Sands WA, and Stone MH. Force-time curve characteristics of dynamic and isometric

543   muscle actions of elite women Olympic weightlifters. *J Strength Cond Res* 19: 741-

544   748, 2005.

545

546   25. Haff GG, Jackson JR, Kawamori N, Carlock JM, Hartman MJ, Kilgore JL, Morris RT,

547   Ramsey MW, Sands WA, and Stone MH. Force-time curve characteristics and

548   hormonal alterations during an eleven-week training period in elite women

549   weightlifters. *J Strength Cond Res* 22: 433-446, 2008.

550

551   26. Haff GG, Ruben RP, Lider J, Twine C, and Cormie P. A comparison of methods for

552   determining the rate of force development during isometric mid-thigh clean pulls. *J*

553   *Strength Cond Res* 29: 386-395, 2015.

554

555   27. Halperin I, Williams KJ, Martin DT, and Chapman DW. The effects of attentional

556   focusing instructions on force production during the isometric midthigh pull. *J Strength*

557   *Cond Res* 30: 919-923, 2016.

558

28. James LP, Roberts LA, Haff GG, Kelly VG, and Beckman EM. Validity and reliability of a portable isometric mid-thigh clean pull. *J Strength Cond Res* 31: 1378-1386, 2017.

559

560

561

29. Kawamori N, Rossi SJ, Justice BD, Haff EE, Pistilli EE, O'Bryant HS, Stone MH, and Haff GG. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J Strength Cond Res* 20: 483-491, 2006.

562

563

564

565

566

30. Kraska JM, Ramsey MW, Haff GG, Fethke N, Sands WA, Stone ME and Stone MH. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sports Physiol Perform* 4: 461-473, 2009.

567

568

569

570

571

31. Maffiuletti N A, Aagaard P, Blazevich A J, Folland J, Tillin N, and Duchateau J. Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol* 116: 1091-1116, 2016.

572

573

574

575

32. Marchetti PH, da Silva JJ, Schoenfeld BJ, Nardi PSM, Pecoraro SL, Greve JMD, and Hartigan E. Muscle activation differs between three different knee joint-angle positions during maximal isometric back squat exercise. *J Sports Med* 2016: 1-6,2016.

576

577

578

579

33. McGuigan MR, and Winchester JB. The relationship between isometric and dynamic strength in college football players. *J Sports Sci Med* 7: 101-105, 2008.

580

581

582

583   34. McGuigan MR, Newton MJ, Winchester JB, and Nelson AG. Relationship between

584   isometric and dynamic strength in recreationally trained men. *J Strength Cond Res* 24

585   : 2570-2573, 2010.

586

587   35. McKinlay BJ, Wallace PJ, Dotan R, Long D, Craig T, Gabriel DA, and Falk B.

588   Isometric and dynamic strength and neuromuscular attributes as predictors of vertical

589   jump performance in 11-13-year-old male athletes. *Appl Physiol Nutr Metab* 42: 924-

590   930, 2017.

591

592   36. Nuzzo JL, McBride JM, Cormie P, and McCaulley GO. Relationship between

593   countermovement jump performance and multijoint isometric and dynamic tests of

594   strength. *J Strength Cond Res* 22: 699-707, 2008.

595

596   37. Owens NJ, Watkins J, Kilduff LP, Bevan HR, and Bennett MA. Development of a

597   criterion method to determine peak mechanical power output in a countermovement

598   jump. *J Strength Cond Res* 28: 1552-1558, 2014.

599

600   38. Pääsuke M, Ereline J, and Gapeyeva H. Knee extension strength and vertical jumping

601   performance in Nordic combined athletes. *J Sports Med Phys Fit* 41: 354-361, 2001.

602

603   39. Rahimi A, Viale F, Dalleau G, and Lacour J-R. Force/velocity and power/velocity

604   relationship in squat exercises. *Eur Appl Physiol* 84: 227 – 232, 2001.

605

606   40. Requena B, Gonzalez-Badillo JJ, Villareal ESS, Ereline J, Garcia I, Gapeyeva H, and

607   Pääsuke M. Functioanl performance, maximal strength and power characteristics in

608   isometric and dynamic actions of lower extremities in soccer players. *J Strength Cond*

609   *Res* 23: 1391-1401, 2009.

610

611

612   41. Sahaly R, Vandewalle H, and Monod DH. Maximal voluntary force and rate of force

613   development in humans – importance of instruction. *Eur J Appl Physiol* 85: 345-350,

614   2001.

615

616   42. Sheppard JM, Chapman D, and Taylor K-L. An evaluation of a strength qualities

617   assessment method for the lower body. *J Australian Strength Cond* 19: 4-10, 2011.

618

619   43. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL,

620   and Hartman M. The importance of isometric maximum strength and peak rate-of-force

621   development in sprint cycling. *J Strength Cond Res* 18: 878-884, 2004.

622

623   44. Thomas C, Jones PA, Rothwell J, Chiang CY, and Comfort P. An investigation into the

624   relationship between maximum isometric strength and vertical jump performance. *J*

625   *Strength Cond Res* 29: 2176-2185, 2015.

626

627   45. Thomas C, Dos'Santos T, Comfort P, and Jones PA. Relationship between isometric

628   strength, sprint and change of direction speed in male academy cricketers. *J Trainology*,

629   5: 18-23, 2016.

630

631   46. Tillin NA, Jimenez-Reyes P, Pain MTG and Folland JP. Neuromuscular performance

632   of explosive power athletes versus untrained individuals. *Med Sci Sports Exerc* 42: 781-

633   790, 2010.

634

635   47. Tillin NA, Pain MTG, and Folland JP. Explosive force production during isometric

636   squats correlates with athletic performance in rugby union players. *J Sport Sci* 31: 66-

637   76, 2013.

638

639   48. Tillin NA, Pain MTG, and Folland JP. Identification of contraction onset during

640   explosive contractions. Response to Thompson et al. "Consistency of rapid muscle

641   force characteristics: influence of muscle contraction onset detection methodology" [J

642   Electromyogr Kinesiol 2012;22(6):893–900]. *J Electromyogr Kinesiol* 23: 991-994,

643   2013b.

644

645   49. Townsend JR, Bender D, Vantrease W, Hudy J, Huet K, Williamson C, Bechke E,

646   Serfini P, and Mangine GT. Isometric mid-thigh pull performance is associated with

647   athletic performance and sprinting kinetics in division 1 men and women's basketball

648   players. *J Strength Cond Res*, 2017. [e-pub ahead of print].

649

650   50. Urquhart M, Bishop C, and Turner AN. Validation of a crane scale for the assessment

651   of portable isometric mid-thigh pulls. *J Australian Strength Cond* 26: 28-33, 2018.

652

653   51. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, La Monica MB, Beyer KS, Church

654   DD, Fukuda DH, and Stout JR. Isometric mid-thigh pull correlates with strength, sprint

655 and agility performance in collegiate rugby union players. *J Strength Cond Res* 30:

656 3051-3056, 2016.

657

658 52. West DJ, Owen NJ, Jones MR, Bracken M, Cook CJ, Cunningham DJ, Shearer DA,

659 Finn CV, Newton RU, Crewther BT, and Kilduff LP. Relationships between force–time

660 characteristics of the isometric midthigh pull and dynamic performance in professional

661 rugby league players. *J Strength Cond Res* 25: 3070–3075, 2011.

662

663 53. Wilson GJ, Lyttle AD, Ostrowski KJ, and Murphy AJ. Assessing dynamic

664 performance: A Comparison of rate of force development tests. *J Strength Cond Res* 9:

665 176-181, 1995.

666

667 54. Wilson GJ, and Murphy AJ. The efficacy of isokinetic, isometric and vertical jump tests

668 in exercise science. *Aust J Sci Med Sport* 27:20-24, 1995.

669

670 55. Zaras ND, Stasinaki AN, Methenitis SK, Krase AA, Karampatsos GP, Georgiadis GV,

671 Spengos KM, and Terzis GD. Rate of Force Development, Muscle Architecture, and

672 Performance in Young Competitive Track and Field Throwers. *J Strength Cond Res*

673 30: 81-92, 2016.

674

Table 1 - ISO instructions

Table 1. *Instructions to collect IS and IMTP data.*

Isometric Mid-Thigh Pull	Isometric Squat
1) Zero the force plate while the athlete is not stood on it.	
2) Set the bar up so the athlete's knee and hip angles are between 130-145 and 140-145°, respectively (as shown in Figure 3). ** Ensure the athletes grip is optimised by using straps and athletic tape.	2) Set the bar up so the athlete's knee and hip angles are between 90-120 and 120-150°, respectively (as shown in Figure 4).
3) Once the athlete has taken their respective position they should be instructed to remain as still as possible without actively pulling or pushing on the bar. 4) Instruct the athlete that following a countdown from 3 they must "focus on pushing the ground as hard and as fast as possible" and continue doing so until told to stop. 5) Acquire a trial length of ~5 seconds which would include a ~2 second quiet stance and ~3-4 second pull. 6) Provide consistent encouragement throughout trials to ensure maximum effort. 7) Analyse the force-time curve to ensure there is no increase in force or a large countermovement before the pull (refer, to figure 5 a and b).	

Appendix 1 – Excel equations relating to defining the onset of the pull.

Cell Name	Equation	Excel calculation
a. Time Point	=1/Sample Frequency	=1/$G$1
b. Baseline weight (N)	= AVERAGE(INDEX(Fz array, Baseline start row):INDEX(Fz array,Baseline end row))	=AVERAGE(INDEX(B:B,G4):INDEX(B:B,G5))
c. F at start (N)	=AVERAGE(INDEX(Fz-BW array, Baseline start row):INDEX(Fz-BW array,Baseline end row))	=AVERAGE(INDEX(C:C,G4):INDEX(C:C,G5))
d. F SD (N)	=STDEV(INDEX(Fz-BW array, Baseline start row):INDEX(Fz-BW array, Baseline end row))	=STDEV(INDEX(C:C,G4):INDEX(C:C,G5))
e. Start of Pull + 5SD (N)	=F at start + (5*Fz SD)	=G10+(5*G11)
f. Start of Pull Cell	=MATCH(Start of Pull + 5SD, Fz-BW array)	=MATCH(G12,C:C)
g. Start of Pull Time (s)	=INDEX(Time array, Start of Pull Cell)	=INDEX(A:A,G13)

*Dollar sign ($) holds the cell column or row prior to it.

Appendix 2. Excel equations to identify whether the trial should be excluded based on minus five standard deviations of the baseline.

Cell Name	Equation	Excel calculation
h. Baseline – 5SD	=F at Start-(5*F SD (N))	= G10-(5*G11)
i. Min. CMv	=MIN(INDEX(Fz-BL (N) ,Baseline End):INDEX(Fz-BL (N) , Start of Pull Cell))	=MIN(INDEX(C:C,G5):INDEX(C:C,G13))
j. Cells from BL End	=MATCH(Min CMv ,INDEX(Fz-BL (N),Baseline End):INDEX(Fz-BL (N), Start of Pull Cell),-1)	=MATCH(J11,INDEX(C:C,G5):INDEX(C:C,G13),-1)
k. Actual Cell	=Baseline End + Cells from BL End	=G5+J12
l. Outcome	=IFS(Min CMv>Baseline-5SD,"Include", Min CMv < Baseline-5SD,"Exclude")	=IFS(J11>J10,"Include",J11<J10,"Exclude")

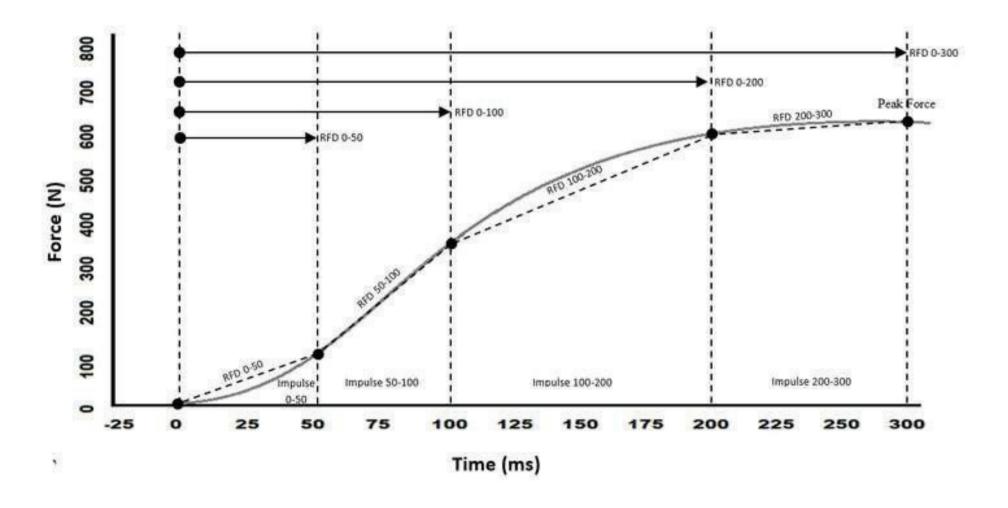**Appendix 3** – Excel equations to extract peak force and time related variables.

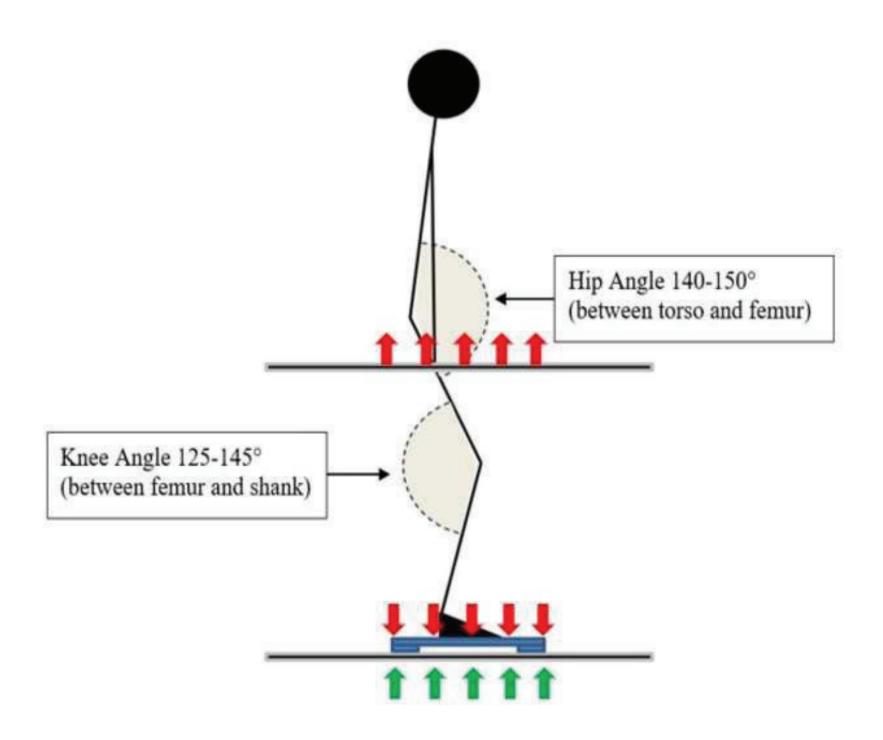| Cell Name	Equation	Excel calculation
m. Fz Max Value (N)	=MAX(Fz-BW array)	=MAX(C:C)
n. Fz Max Cell	=MATCH(Fz Max Value,Fz-BW array, 0)	=MATCH(G16,C:C,0)
o. Fz Max Time (s)	=INDEX(Time array, Fz Max Cell)	=INDEX(A:A,G17)
p. Time to Fz Max (s)	=Fz Max Time – Start of Pull Time	=G18-G14
RFD, Force at specific time points and Impulse.	All RFD, force at specific time points and impulse measures, with the exception of aRFD can be repeated to extract information on the required epoch's . Alternatively, users can manually change the time value to obtain epochs.	
q. Average RFD (N·s)	=Fz Max Value / Time of Fz Max	=G16/G19
r. Time at above (s)	= Start of Pull Time + RFD @	=$G$14+G23
s. Cell of above	=MATCH(Time at above, Time array,1)	=MATCH(G24,A:A,1)

t. Fz of above (N)	=INDEX(Fz-BW array, Cell of above)	=INDEX(C:C,G25)
u. RFD of above (N·s)	=(Fz of above - Start of Pull + 5SD)/RFD @	=($G$26-$G$12)/G23
v. RFD 0.1 -0.2 s (Ns)	=(Fz of above at RFD 0.1 -Fz of above at RFD 0.2)/Time intervals	=(G33-G26)/$G$44
w. Impulse (Column D)	=(AVERAGE(Fz-BL:Fz-BL))/(1*sample frequency)	=(AVERAGE(C2:C3))/(1*$G$1)
x. Impulse of above (N·s)	=SUM(INDEX(Impulse array, Start of Pull Cell):INDEX(Impulse array, Cell of above))	=SUM(INDEX(D:D,G13):INDEX(D:D,G25))
y. Impulse 0.1-0.2 (Ns)	=SUM(INDEX(Impulse array, Cell of above at RFD 0.1):INDEX(Impulse array, Cell of above at RFD 0.2))	=SUM(INDEX(D:D,G25):INDEX(D:D,G32))

*Dollar sign ($) holds the cell column or row prior to it.

Figure 2

Figure 2

Figure 3

Hip Angle 140-150°
(between torso and femur)

Knee Angle 125-145°
(between femur and shank)

Figure 4

Hip Angle 135-140°
(between torso and femur)

Knee Angle 135- 140°
(between femur and shank)
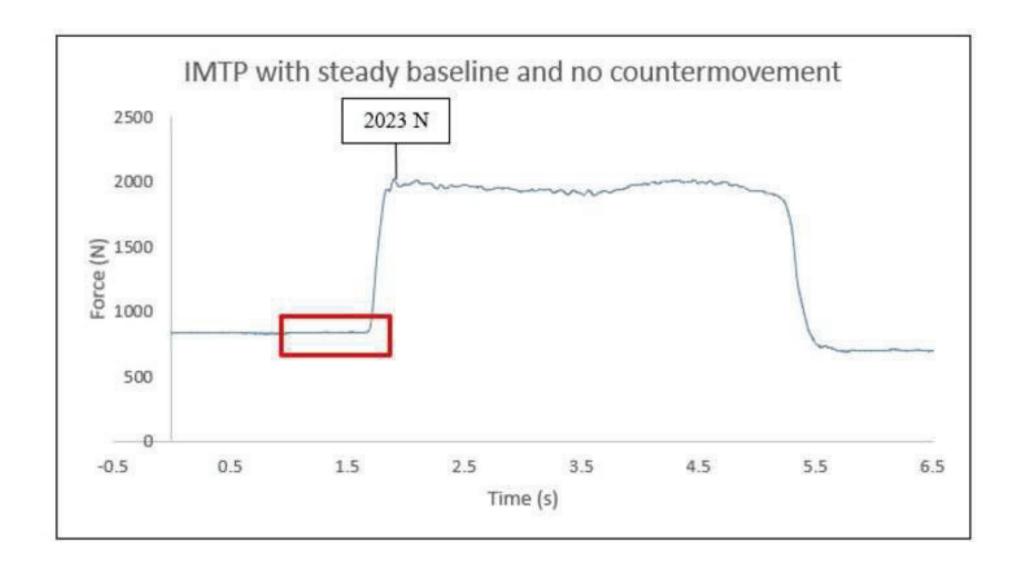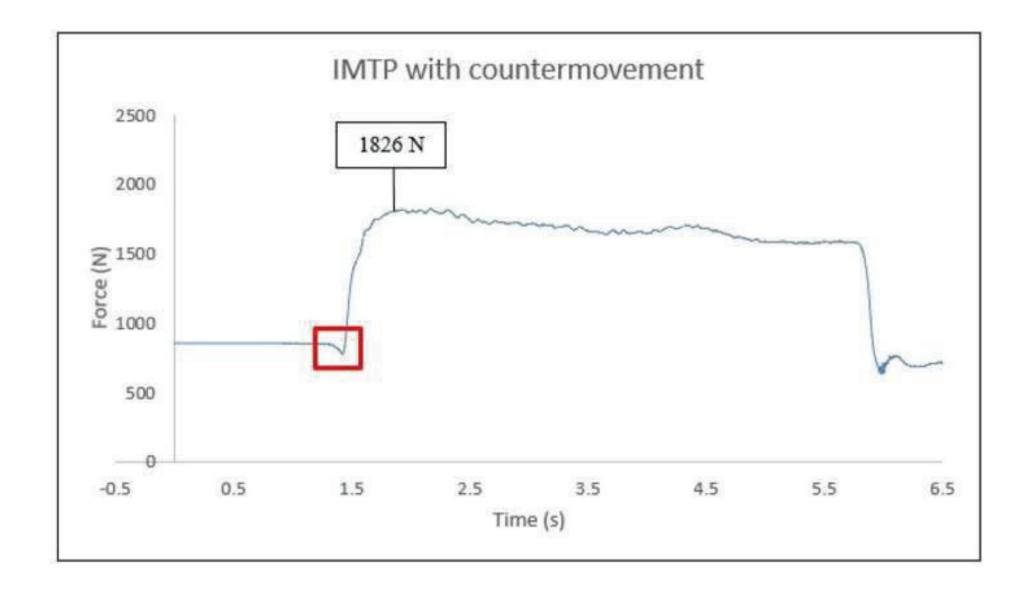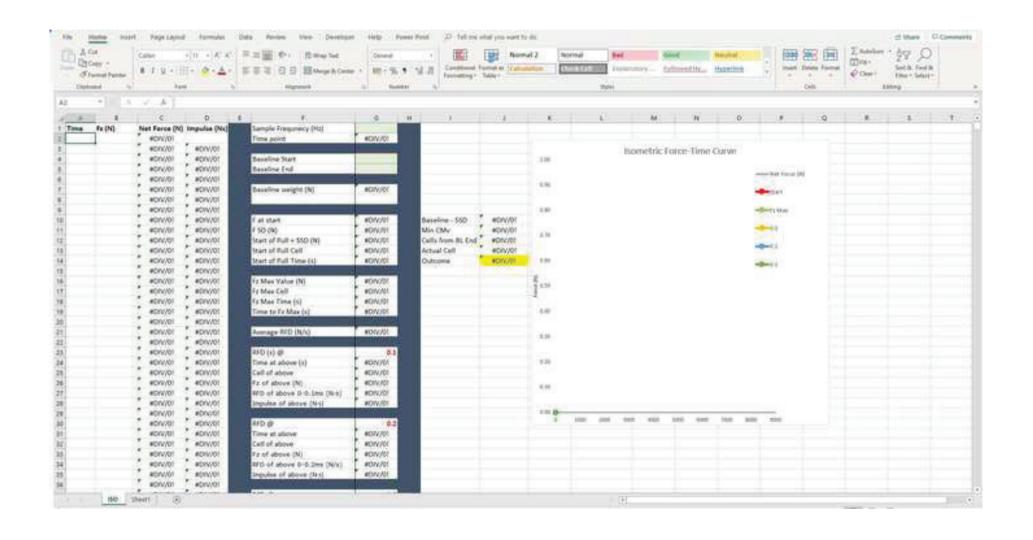
IMTP with steady baseline and no countermovement

IMTP with countermovement

Figure 7

Isometric Force-Time Curve