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Journal of Sports Sciences

Backward Double Integration is a Valid Method to Calculate Maximal and Sub-Maximal Jump Height --Manuscript Draft--

Full Title:	Backward Double Integration is a Valid Method to Calculate Maximal and Sub-Maximal Jump Height
Manuscript Number:	RJSP-2021-1518R1
Article Type:	Original Manuscript
Keywords:	Countermovement jump; squat jump; Drop jump; Force Plate; vertical jump
Abstract:	<p>The backward double integration (BDI) method uses one force plate and could calculate jump height for all jumping types (countermovement, squat and drop jump) by analysing the landing phase, instead of the push-off phase. This study examined the accuracy of the BDI method against the reference forward double integration (FDI) method, as well as the Flight Time + Constant (FT+C) method. It was hypothesised that the BDI method would calculate jump height with a similar accuracy to the FDI method, while the FT+C method would have reduced accuracy and increased variability during sub-maximal jumping. Twenty-four volunteers performed five maximal and sub-maximal countermovement jumps, while ground reaction force data were collected. Bland-Altman and correlation analyses examined differences in jump height calculated on the same jump between methods. BDI obtained similar mean jump height values as the FDI method and therefore can be used in situations where FDI cannot be employed (i.e. squat jumping and drop jumping). While the FT+C method had a higher variability than BDI, this method was able to account for changes in jumping intensity without a decrease in accuracy, further strengthening the notion that this method can be used to calculate jump height in the field.</p>
Order of Authors:	Logan Wade Laurie Needham M. Polly McGuigan James L. J. Bilzon
Response to Reviewers:	<p>We would like to thank both reviewers for their valuable insight into this manuscript and believe the changes made to the manuscript have considerably increased the value and strength of this work. We have included a rigid-body kinematic modelling method and as such, have edited much of the manuscript to fit these changes in. The main changes relating to comments from both reviewers have been highlighted in red for clarity.</p> <p>Reviewer 1 Reviewer: Force plates are used in the field to determine jump height by double integration. In the ideal Newtonian world, this is straightforward and works like a charm. In the real world, it is notoriously unreliable because force plates do not work perfectly and small errors blow up due to integration drift. Therefore, the golden standard is jump height determined from kinematics, which does not suffer from integration drift. In cases where only a force plate is available, the advice is to use trim the force records as much as possible. In squat jumping, however, the sections for FDI are still long, and in drop jumping no section for FDI is available. To solve these problems, BDI using the landing phase has been proposed by Wank and Coenning (2019), which in the ideal world will work just as good as FDI to determine jump height. And in fact, those authors have shown that BDI yields the same jump height as full body kinematics.</p> <p>The authors of the current manuscript set out to determine whether the Backward Double Integration is a *valid* method to calculate maximal and sub-maximal jump height. There is no doubt about that, this has already been shown by Wank and Coenning (2019); they performed an *actual validation* by comparing the calculated</p>

jump height with jump height determined from kinematics. There is also no reason to doubt that this is true just as well for maximal and submaximal jumps. The authors of the current manuscript did not perform an actual validation, because jump height calculated from BDI was compared to jump height calculated from FDI, with both being prone to error due to integration drift. It is possible for an individual jump that FDI overestimates the true jump height by several cm and that BDI underestimates jump height by several cm. If the errors due to integration drift are random, the mean values of jump height over many jumps will surely be the same, but in my opinion, that is not a sound way to determine whether the BDI method is valid, nor a good method to estimate the variability of the BDI method.

Response: We originally collected marker-based kinematic data along with the force plate data. However, we decided not to include a kinematic comparison to facilitate a direct comparison between the BDI and FDI methods. However, we now see that a reference method, which is not dependent on force data (kinematic method), is needed to compare the BDI and FDI methods, which was the primary aim of this paper. As such, we have reprocessed the Bland-Altman and correlation analysis using rigid-body modelling as the reference method (Lines 163 and Line 168).

We do not dispute that Wank and Coenning (2019) demonstrated that BDI is a valid method to examine jump height and therefore have further stressed this point in the manuscript (Line 116-119). However, we must note that comparisons between methods using paired t-tests only proves that the kinematic and BDI methods are not statistically different, it does not indicate that they are the same as you have stated. Comparisons to identify the magnitude of the bias (accuracy) and SD of the bias (variability) between methods using statistical analysis such as Bland-Altman analysis and correlation analysis are needed. Furthermore, Wank and Coenning (2019) performed pairwise comparison on the absolute values and therefore variability of the BDI method is unknown. On average, this method may appear accurate but individual results may have large variability that is lost due to analysis of absolute mean jump height values We have included this rational within the text (Line 120).

Both double integration and marker-based methods have well known errors, and thus we do not believe a gold standard for calculating jump height exists. Marker-based errors have been added to the manuscript (Line 76). However, we see the value in having a measure that is independent from force plates to compare BDI and FDI, and believe the updated manuscript is now much more thorough. The comparison between BDI and FDI, not validation of the BDI, was the main aim of this paper, although this was not clearly defined due to lack of including a separate method for calculating jump height (kinematic method). Therefore, this has been added to the manuscript to improve clarity (Line 121).

Finally, we did not believe that the BDI or FDI methods would have reduced accuracy or variability during sub-maximal jumping compared to maximal jumping. The addition of this condition was primarily to examine if the FT+C method would have reduced accuracy and variability due to employing a constant heel-lift distance, while actual heel-lift distance decreased during sub-maximal jumping relative to maximal jumping. The manuscript has been altered to further clarify this point (Line 135)

Line 163:

Motion capture data was recorded using a 15-camera Qualisys motion capture system (Oqus, Qualysis, Gothenburg, Sweden) at 200 Hz. A full body marker-set consisting of 44 individual makers and eight clusters were attached to participants, with a full description of marker locations detailed in 1.

Line 168:

Visual 3D (C-Motion, Maryland, USA), where rigid-body, six degrees of freedom, kinematic modelling was performed to calculate displacement of the centre of mass (Kinematic Method). GRF and COM displacement calculated using rigid-body modelling was imported into Python 3.7 where a custom script calculated jump height using the Kinematic Method, FDI method, BDI method and the FT+C method.

Line 116:

Currently, only one study has examined the accuracy of BDI method, which calculated

jump height during drop jumping and compared the BDI method to marker-based kinematic modelling. Using paired t-tests, they found that results between methods were not statistically different and therefore the BDI was a valid method for calculating jump height.

Line 120:

However, pairwise testing can only determine if a significant difference exists, not that two methods produce the same results for method accuracy and variability. Finally, it is also valuable to know if the FDI and BDI methods produce equivalent results and could be used interchangeably, although this can only be tested on countermovement jumping as FDI cannot be used with drop jumping or squat jumping.

Line 76:

While this method performs strongly at calculating jump height, it has been shown to overestimate flight distance and underestimate heel-lift distance 2, 3, in addition to joint centre location errors that may be up to 30 mm 4.

Line 121:

Finally, it is valuable to know if the FDI and BDI methods produce equivalent results and could be used interchangeably, although this can only be tested on countermovement jumping as FDI cannot be used with drop jumping or squat jumping. Therefore, the first aim of this study was to build previous work by comparing individual sub-maximal and maximal countermovement jump heights calculated using the FDI, BDI and FT+C methods against marker-based rigid-body kinematic modelling methods, which were not dependent on force plate data and could therefore be used as a reference method. We believe results obtained during countermovement jumping of this study are directly comparable to drop jumping and squat jumping as landing phases in these jumps should be identical. It was hypothesised that the BDI method would demonstrate equivalent accuracy and variability compared to the FDI and the FT+C method would have reduced accuracy compared to the BDI and FDI methods.

Line 135

However, there is potential for increased movement variability during sub-maximal movements and while the FDI and BDI method are unlikely to be affected by different jump intensities, the FT+C method uses a participant-specific anthropometrically scaled heel-lift constant that does not change, irrespective of the jumping intensity. Therefore, it is likely that during sub-maximal jumping, heel-lift distance will be decreased and produced with greater variability, which may reduce the accuracy of the FT+C method during sub-maximal jumping. The second aim of this study was to examine if jump height calculated with the FT+C method, as well as the FDI and BDI, have reduced accuracy during sub-maximal jumping compared to maximal jumping. It was hypothesised that while the FDI and BDI method would not be affected, the FT+C method would overestimate jump height and have greater variability during sub-maximal jumping compared to maximal jumping.

Reviewer: Furthermore, the authors only compared FDI and BDI for countermovement jumping, and hence they should not draw a *conclusion* with respect to squat jumping and drop jumping. In the ideal Newtonian world, this is true, the method is valid. We do not need the results of the current study to establish this, unless there is theory saying that force plates have a different accuracy in push-off than landing.

Response: Comparing between jump heights of the same jump, using both BDI and FDI methods relative to rigid-body kinematic modelling methods, we have demonstrated that BDI may have slightly increased variability compared to FDI method, although this effect is very small (Line 302). Furthermore, we have found that landing takes longer to perform on average than push-off, which may have contributed to the BDI slight increase in variability (Line 310).

However, we do acknowledge that this comparison was only performed in countermovement jumping and therefore have included a statement that acknowledges that this (Line 314). However, as long as the landing phases of each jumping type are kept the same, then we see no reason why analysing these methods using

countermovement jumping is not directly comparable to squat and drop jumping.

Line 302:

These results reinforce the finding from Wank and Coenning 5, and also support our first hypothesis, demonstrating that jump height calculated using the FDI and BDI methods are on average equivalent and could be used interchangeably, although BDI may have slightly higher variability compared to the FDI method (Table 1 - SD of Bias and 95% LoA). For both BDI and FDI methods, Cohen's d effect sizes were classified as trivial and confidence intervals overlapped with zero, indicating no differences compared to rigid-body kinematic modelling methods on average (Figure 2).

Line 310:

The landing time for the BDI method was on average greater by 0.3 s compared to the push-off time for the FDI method, and therefore it is possible that the slightly longer time to return to normal standing during landing may result in greater variability of this method, however the effect was very small.

Line 314:

It must be noted that while landing phases of countermovement jumping, squat jumping and drop jump should be identical, this study only examined countermovement jumping and this ought to be kept in mind when applying these methods to alternative jumping types.

Reviewer: In sum, although the authors have diligently collected and processed their data and clearly communicated what they have done and found, I feel that their manuscript does not advance our knowledge in the field. Validation of a method to determine jump height with force plates only, should use jump height determined by kinematics as the golden standard. The same is true for determining the amount of heel lift at takeoff or landing in maximal and submaximal jumps.

Response: Unfortunately, multiple previous studies have determined that heel-lift and flight distance calculated using kinematic measures are prone to error 2, 3 and furthermore, analysis of marker-based methods have demonstrated kinematic joint centre location errors of up to 30mm 4. This has been added to the text for clarity (Line 93). Therefore, it is unwise to classify that marker-based methods are a gold standard when there are known errors. Force integration minimises much of these issues and without comparison to a true gold standard such as bi-planar radiovideography (which is currently not possible due to capture volume), we must accept that there is no gold standard for measuring jump height at this time.

However, without a common method with which to compare BDI and FDI methods that does not rely on force plates, we agree with the reviewer that it is not possible to draw conclusion about the accuracy and variability of the BDI method and thus have added a marker-based rigid body modelling method to serve as a reference and enable comparison between the BDI, FDI and FT+C methods.

Line 76:

While this method performs strongly at calculating jump height, it has been shown to overestimate flight distance and underestimate heel-lift distance 2, 3, in addition to joint centre location errors that may be up to 30 mm 4.

Reviewer 2

Reviewer: I think that there are a lot of readers, who are not very well versed in biomechanics, that could slightly struggle with the concepts in the paper. Perhaps, you could stress even more clearly in the section in lines 29-33, that the jump height calculated from take-off velocity and flight time are not accurate, because they neglect 8-10 cm heel-raise. Perhaps, in the line 33, an additional sentence along these lines: "Calculations based on flight time or take-off velocity neglect the heel-raise and

therefore underestimates the jump height". In this sentence (and perhaps elsewhere), I would add the reference by Chiu (2020). They describe and research this issue nicely. Chiu, L. Z., & Dæhlin, T. E. (2020). Comparing numerical methods to estimate vertical jump height using a force platform. *Measurement in Physical Education and Exercise Science*, 24(1), 25-32.

Response: Thank you for your insight, we have added a sentence and this reference into this section stressing this point.

Line 34:

As such, methods for calculating jump height that do not take heel-lift into account will substantially underestimate jump height 3, 6, 7.

Reviewer: Consider including some numerical information into the abstract, maybe at least for the most important finding (i.e., related to line 15-16)

Response: We have added the two most important outcome measures to the abstract

Reviewer: Line 151-152: This information is repeated from line 147

Response: This sentence has been removed

Reviewer: Line 168-170: perhaps a reference and explanation could be provided regarding this choice

Response: This was the method outlined by Vanrenterghem, De Clercq 8. The text has been adjusted and reference inserted.

Line 183:

Following the methods outlined by Vanrenterghem, De Clercq,

Reviewer: Can you please provide (very briefly) some more details on participants (e.g., were they physically active, were they familiar with jumping assessments?). Perhaps the proficiency in control of the jump could affect the results (you alluded to that - Line 301-303).

Response: Text has been added to Line 148 to improve clarity on this issue

Line 148:

Twenty-three healthy participants (11 female and 12 male, age = 28 ± 5 years, mass = 70 ± 12 kg, height = 172 ± 9 cm) without any formal jumping training gave written informed consent to participate in this study.

Reviewer: If I understand correctly, you combined all of the jumps (5 jumps x 24 subject) into the analysis (in other words, there were 120 cases for the analysis?) Or was the average (or the best) jump taken? In any case, it should be made clearer

Response: Text has been added to the manuscript on Line 175 to improve clarity on this issue

Line 175:

Thus, for all methods, 109 maximal jumping trials and 110 sub-maximal jumping trials were analysed using pairwise comparison.

Reviewer: Table 1: I miss perhaps an additional measure like SEM or typical error, expressed as % of the mean; it puts the bias into a more relative perspective and is easier to interpret

Response: The Bland-Altman 95% limits of agreement is potentially better at demonstrating absolute reliability than a measure such as SEM as it encompasses 95% of the data. Additionally, users of these methods for real world applications need to know the absolute values of variance that could be expected (cm), in order to determine if the variance is acceptable to their application. Finally, because there are no gold standard methods for calculating jump height, the % differences of BDI and FDI relative to the Kinematic method are not the primary outcome. Instead, the differences between the BDI and the FDI methods are the key outcome measure and thus measurements in cm are of the most value. For these reasons we have decided not to include a measure of variance expressed as a percentage.

Reviewer: Line 232: Is this Pearson correlation? Please clarify. I think ICC with absolute agreement model might be more appropriate for this type of study.

Response: This is the R² (coefficient of determination), which represents the reliability of the linear relationship between two individuals. This was not clear in the manuscript and has been adjusted in text (Line 257).

Thank you for your suggestion on the application of the ICC with absolute agreement. We have added this to the analysis as can be seen in Table 1 and Line 257.

Line 257

Pearson coefficient of determination (R²), estimation statistics and intraclass correlation using the absolute agreement method were also calculated, including Cohen's d effect size with bootstrapped confidence intervals (CI) 10.

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1 Backward Double Integration is a Valid Method to Calculate Maximal and Sub-Maximal
2 Jump Height

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35 13 **Word Count:** 4023

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38 14 **Abstract Word Count:** 194

21 **Abstract**

22 The backward double integration method uses one force plate and could calculate jump height
23 for countermovement jumping, squat jumping and drop jumping by analysing the landing phase
24 instead of the push-off phase. This study compared the accuracy and variability of the forward
25 double integration (FDI), backwards double integration (BDI) and Flight Time + Constant
26 (FT+C) methods, against the marker-based rigid-body modelling method. It was hypothesised
27 that jump height calculated with the BDI method would be equivalent to the FDI method, while
28 the FT+C method would have reduced accuracy and increased variability during sub-maximal
29 jumping compared to maximal jumping. Twenty-four volunteers performed five maximal and
30 sub-maximal countermovement jumps, while force plate and motion capture data were
31 collected. The BDI method calculated equivalent mean jump heights to the FDI method, with
32 only slightly higher variability (2-3 mm), and therefore can be used in situations where FDI
33 cannot be employed. The FT+C method was able to account for reduced heel-lift distance,
34 despite employing an anthropometrically scaled heel-lift constant. However, across both sub-
35 maximal and maximal jumping, it had increased variability (1.1 cm) compared to FDI and BDI
36 and should not be used when alternate methods are available.

38 **Keywords**

39 Countermovement jump, squat jump, drop jump, force plate, vertical jump, flight time

43 Introduction

44 Jump height is often used to estimate athletic lower limb neuromuscular capabilities during
45 training ^{1, 2} and rehabilitation ³. Additionally, jump height is commonly used to explore
46 foundational human movement, as it requires coordination from multiple joints and can be
47 performed across a range of intensities ^{4,5}. We defined jump height as the distance between the
48 centre of mass (CoM) during standing and the apex of the jump, as this period includes all the
49 work performed to propel the CoM into the air. The measure requires the jumper to break
50 contact with the ground and therefore due to heel-raise commonly lifting the centre of mass 8-
51 10cm ⁶⁻⁹, a jump height below this height is very uncommon. **As such, methods for calculating
52 jump height that do not take heel-lift into account will substantially underestimate jump height
53 7, 10, 11**. Countermovement jump height is commonly used in power estimation formulas as an
54 estimate of athlete power output^{12, 13}, and the countermovement, squat and drop jump are often
55 compared to examine neuromuscular functional capabilities¹⁴⁻¹⁶. However, comparing jump
56 height between jump types can be difficult as methods for calculating jump height may be
57 influenced by different starting positions^{4, 17}.

58
59 One of the most accessible and reliable jump height calculation methods is the forward double
60 integration (FDI) method, which only requires a single force plate and calculates jump height
61 using the ground reaction force (GRF) trace during push off ¹⁸. The net GRF trace is divided
62 by body mass to calculate CoM acceleration, which is integrated once to calculate CoM
63 velocity and then integrated a second time to calculate CoM displacement at take-off (heel-lift
64 distance). CoM velocity at take-off is input into a projectile motion equation to calculate
65 distance travelled in the air, which is finally summed with the heel-lift distance to calculate
66 jump height. Previous research has demonstrated that using an average body mass for all
67 jumping trials should not be employed, as it can result in jump height errors of up to 4.5 cm ¹⁹.

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68 Therefore, the FDI method requires an accurate measure of bodyweight and position of the
69 CoM for every jump, calculated by participants stand as still as possible prior to push-off ¹⁹.
70 Additionally, the period over which FDI is performed needs to be kept as small as possible, so
71 that minute GRF errors do not have time to be exponentially amplified by double integration,
72 which can cause large heel-lift distance errors ¹⁰. Maximal countermovement jumping
73 generally takes about 1 second to perform (end of quiet standing until take-off), which is
74 generally small enough to limit substantial amplification of heel-lift distance errors. However,
75 calculating jump height during squat jumping can result in large heel-lift distance errors, as
76 participants are required to descend and hold the squatted position before performing the jump.
77 The entire jump (end of quiet standing until take-off) can take up to 4-6 seconds and as such,
78 squat jump height should not be calculated using the FDI method ¹⁰. Alternatively, drop
79 jumping requires participants to start on a box next to the force plate and drop down onto it,
80 thus information about participant bodyweight and location of the CoM during quiet standing
81 is missing. This issue can be overcome by placing a second force plate on the drop box or
82 placing the drop box on a force platform to calculate bodyweight and CoM height during quiet
83 standing. If using two force plates, the data from both force plates can then be combined and
84 the FDI method is performed as normal, after which the output is summed with the known
85 height of the drop box to calculate jump height ²⁰. However, this method requires an additional
86 portable force plate to be placed on the drop box, or a single force plate is needed that is large
87 enough to fit both a drop box and space to perform jumping. Due to the errors present when
88 using FDI to measure squat jumping and the additional equipment required to measure jump
89 height during drop jumping, alternative methods are necessary.

90

91 Three-dimensional marker-based motion capture, combined with rigid-body modelling, has
92 commonly been used in laboratories to calculate displacement of the CoM during jumping ²¹.

93 While this method performs strongly at calculating jump height, it has been shown to
94 overestimate flight distance and underestimate heel-lift distance^{10,22}, in addition to joint centre
95 location errors that may be up to 30 mm²³. Furthermore, this method requires a substantial
96 amount of additional equipment, software and complex post-processing of data that is far
97 beyond what may be required for many practical applications of jump height. Wade, Lichtwark
98 and Farris¹⁰ detailed a hybrid method that combines marker-based motion capture with force
99 plates to calculate jump height without time intensive processing of the data and complex rigid-
100 body modelling. However, due to the additional equipment required for this method, it is
101 primarily limited to application in a laboratory setting.

102
103 A simple and cost-effective alternative is the flight time (FT) method, which only requires the
104 time in the air between take-off and landing to be obtained and can be performed with a single
105 force plate, pressure mat¹⁸ or even a smartphone²⁴. It is commonly used in field applications
106 to assess countermovement jumping, drop jumping and squat jumping, as the flight phases of
107 each are identical. However, the FT method is not a true measure of jump height as it does not
108 take heel-lift into account, therefore this method consistently underestimates jump height by
109 approximately 8-10 cm depending on the individual^{7,25}. Furthermore, the FT method assumes
110 the position of the CoM is the same at take-off and during landing, which is never the case as
111 the legs adopt a more flexed position during landing to attenuate landing forces²². Previous
112 research has demonstrated that an anthropometrically scaled constant, based on each
113 participant's foot length, may be used as a substitute for heel-lift distance. The constant is then
114 summed with distance travelled in the air calculated by the FT method to estimate jump height
115¹⁰. While the FT plus heel-lift constant (FT+C) method demonstrated a substantial
116 improvement compared to the FT method alone¹⁰, the heel-lift distance during sub-maximal
117 jumping or between countermovement jumping, squat jumping and drop jumping may be

118 inconsistent due to altered coordination strategies. An alternative method that only uses a single
119 force plate and can calculate jump height from any jump type could facilitate improved
120 accuracy for coaches and researchers examining jumping.

121

122 The backwards double integration (BDI) method calculates jump height using the same method
123 as FDI method, except instead of integrating over the push-off phase, integration is performed
124 over the landing phase^{20, 26}. Jumping starts and ends in a quiet standing position, therefore all
125 the energy generated to propel the CoM upwards must be attenuated during landing. Using the
126 BDI method, jump height could be calculated for countermovement jumping, squat jumping
127 and drop jumping, as the landing phases of these three jump types are performed exactly the
128 same (i.e. landing that is followed immediately by return to quiet standing). It should be noted
129 that BDI cannot calculate CoM distance travelled in the air or heel-lift distance, as this method
130 is measuring the landing phase, however this does not impede its ability to calculate jump
131 height. Additionally, portable force plates may struggle with this method due very high peak
132 ground reaction forces during landing, which can produce clipping of the forces due to maxing
133 out the force plate. Currently, only one study has examined the accuracy of the BDI method,
134 performing analysis during drop jumping and comparing the BDI method to marker-based
135 kinematic modelling. Using paired t-tests, they found that results between methods were not
136 statistically different and therefore the BDI was a valid method for calculating jump height.
137 However, pairwise testing can only determine if a significant difference exists, not that two
138 methods produce the same results for accuracy and variability. Finally, it is valuable to know
139 if the FDI and BDI methods produce equivalent results and could be used interchangeably,
140 although this can only be tested on countermovement jumping as FDI cannot be used with drop
141 jumping or squat jumping. Therefore, the first aim of this study was to build previous work²⁰
142 by comparing individual sub-maximal and maximal countermovement jump heights calculated

143 using the FDI, BDI and FT+C methods against marker-based rigid-body kinematic modelling
144 methods, which were not dependent on force plate data and could therefore be used as a
145 reference method. We believe results obtained during countermovement jumping of this study
146 are directly comparable to drop jumping and squat jumping as landing phases in these jumps
147 should be identical. It was hypothesised that the BDI method would demonstrate equivalent
148 accuracy and variability compared to the FDI and the FT+C method would have reduced
149 accuracy compared to the BDI and FDI methods.

150

151 Sub-maximal jump heights are often be used to explore how complex full body movements are
152 executed ^{5, 6}. However, there is potential for increased movement variability during sub-
153 maximal movements and while the FDI and BDI method are unlikely to be affected by different
154 jump intensities, the FT+C method uses a participant-specific anthropometrically scaled heel-
155 lift constant that does not change, irrespective of the jumping intensity. Therefore, it is likely
156 that during sub-maximal jumping, heel-lift distance will be decreased and produced with
157 greater variability, which may reduce the accuracy of the FT+C method during sub-maximal
158 jumping. The second aim of this study was to examine if jump height calculated with the FT+C
159 method, as well as the FDI and BDI, have reduced accuracy during sub-maximal jumping
160 compared to maximal jumping. It was hypothesised that while the FDI and BDI method would
161 not be affected, the FT+C method would overestimate jump height and have greater variability
162 during sub-maximal jumping compared to maximal jumping.

163

164 **Methods**

165 Twenty-three healthy participants (11 female and 12 male, age = 28 ± 5 years, mass = 70 ± 12
166 kg, height = 172 ± 9 cm) without any formal jumping training gave written informed consent

167 to participate in this study. Ethics was approved by the University of Bath, Research Ethics
168 Approval Committee for Health (EP 18/19 053). Participants attended the Applied
169 Biomechanics Suite at the University of Bath on a single occasion and performed jumping in
170 their own shoes. After a self-directed warmup, participants completed five sub-maximal
171 countermovement jumps and five maximal countermovement jumps assigned in a block
172 randomised order. During maximal jumping, participants were asked to jump maximally, while
173 during sub-maximal jumping, participants were asked to jump at 50% maximal effort. For each
174 trial, participants started off the force plate while it was zeroed and then stepped onto two force
175 plates (one foot on each plate), where they assumed a quiet standing position with their arms
176 on their hips (no arm swing during jumping). Participants stood still for 2-3 seconds before
177 performing either a sub-maximal or maximal countermovement jump. Upon landing they were
178 told to resume their quiet standing position, at which point data collection was terminated.

179
180 Motion capture data was recorded using a 15-camera Qualisys motion capture system (Oqus,
181 Qualysis, Gothenburg, Sweden) at 200 Hz. A full body marker-set consisting of 44 individual
182 makers and eight clusters were attached to participants, with a full description of marker
183 locations detailed in ²⁷. GRF data were collected from two in-ground force plates (Kistler
184 9287CA, Winterthur, Switzerland) at 1000 Hz. Motion capture data and GRF data were
185 collected in Qualisys Track Manager (QTM, Qualisys, Sweden) and then exported to Visual
186 3D (C-Motion, Maryland, USA), where rigid-body, six degrees of freedom, kinematic
187 modelling was performed to calculate displacement of the centre of mass (Kinematic Method).
188 GRF and CoM displacement calculated using rigid-body modelling was imported into Python
189 3.7 where a custom script calculated jump height using the Kinematic Method, FDI method,
190 BDI method and the FT+C method. During data processing, all trials that did not end with the
191 participant standing quietly on the plate were excluded, resulting in 21 of 240 trials being

192 excluded. Thus, for all methods, 109 maximal jumping trials and 110 sub-maximal jumping
193 trials were analysed using pairwise comparison.

194

195 Forward Double Integration (FDI)

196 The vertical GRF traces from each plate were combined and the average GRF during the time
197 in the air was subtracted from the entire GRF trace to digitally zero the force plate. The quiet
198 standing period was identified, and bodyweight was calculated by taking a mean value over
199 one second (Figure 1). Net GRF was then obtained by subtracting bodyweight from the zeroed
200 GRF trace. Following the methods outlined by Vanrenterghem, De Clercq¹⁹, the net GRF trace
201 and the same period that bodyweight was calculated over were used to identify, net GRF
202 maximum, minimum and standard deviation (SD). To identify start of the countermovement
203 after quiet standing, the first value that exceeded either the maximum + one SD or the minimum
204 – one SD was identified. Working backwards, the first value that exceeded 0 N (either positive
205 or negative) was identified as the start of the countermovement (Figure 1)¹⁹. Take-off was
206 identified as the first point the net GRF trace exceeded negative bodyweight following push-
207 off (Figure 1). To calculate jump height, the net GRF trace was divided by body mass
208 (bodyweight/gravity) to calculate CoM acceleration. The CoM acceleration trace was
209 integrated (trapezoidal) to calculate CoM velocity which was then subsequently integrated to
210 calculate CoM displacement at take-off (heel-lift). The final value of the CoM velocity trace
211 was used to calculate distance travelled in the air using the projectile motion equation:

$$v^2 = u^2 + 2as$$

212
213 Where v equals the velocity at take-off, u equals the velocity at the apex of the jump (0 m/s), a
214 equal's gravity (9.81 m/s²) and s equals the distance travelled in the air. The distance travelled
215 in the air and heel-lift distance were then summed to calculate jump height. Within-participant

216 heel-lift averages and SD's were calculated by taking the mean value of the heel-lift distance
217 or SD for each individual participant, within each jump condition (sub-maximal and maximal).

218

219 Backwards Double Integration (BDI)

220 Using the same initial protocol as FDI, vertical GRF and the zeroed GRF trace were calculated.

221 Bodyweight was calculated by starting from the last data point and moving backwards to

222 identify the quiet standing period immediately after landing (0.5 seconds of quiet standing) at

223 which point the GRF trace was averaged (Figure 1). Net GRF was calculated by subtracting

224 bodyweight from the zeroed GRF and then net GRF maximum, minimum and SD values during

225 quiet standing were identified. Working backwards from the end of the trial, the first value that

226 exceeded the maximum + one SD or the minimum - one SD was obtained. Then moving

227 forward, the last point that exceeded 0 N (positive or negative) was identified as the end of the

228 landing phase (i.e. quiet standing, Figure 1). Start of landing was identified as first value to

229 exceed negative bodyweight after push-off (Figure 1). The net GRF trace was trimmed from

230 the start of landing to the end of landing and then reversed so that sequentially, end of landing

231 occurred before start of landing. From this point, the FDI method was repeated by calculating

232 CoM acceleration, performing double integration of the CoM acceleration trace, calculating

233 distance travelled in the air using projectile motion and summed this value with CoM

234 displacement at landing to calculate jump height.

235

236 **Kinematic Rigid-Body Modelling**

237 Displacement of the CoM calculated in Visual3D was imported into Python 3.7. Standing

238 height was calculated as the average height of the CoM for 300 ms prior to the start of push-

239 off, using event timing calculated by the FDI method. Maximal height of the CoM was then

240 obtained (apex of the jump) and the average standing height was subtracted from the maximal
241 CoM height to calculate jump height. Leg length comparison between sub-maximal and
242 maximal jumping was performed by calculating the vertical position of the centre of mass of
243 the pelvis at landing. The average vertical position between the distal ends of the right and left
244 foot were then calculated and subtracted from the pelvis COM position to calculate leg length.

245

246 Flight Time + Constant (FT+C)

247 The FT method calculated the CoM distance travelled in the air by using take-off (FDI) and
248 landing events (BDI) calculated previously. Time in the air was halved and then input into the
249 projectile motion equation:

$$s = ut + \frac{1}{2}at^2$$

252 Where s equals the distance travelled in the air, u equals the velocity at the apex of the jump (0
253 m/s), a equal's gravity (9.81 m/s²) and t equals half the time in the air. Heel-lift constant was
254 calculated by taking foot measurements using a tape measure which were input in to the
255 formula created by Wade, Lichtwark and Farris ¹⁰

$$Constant = (0.88 \times Foot Length) + Sole Thickness - Ankle Height$$

257 Where *Foot Length* equals the distance between the medial malleoli and the tip of the shoe,
258 *Sole Thickness* equals the thickness of the sole inferior to the 1st phalangeal joint and *Ankle*
259 *Height* equals the distance between the medial malleoli and the ground. All measurements were
260 taken immediately after performing jumping and participants kept their shoes on. Distance
261 travelled in the air for each trial was then summed with each participant's anthropometrically
262 scaled heel-lift constant to calculate jump height.

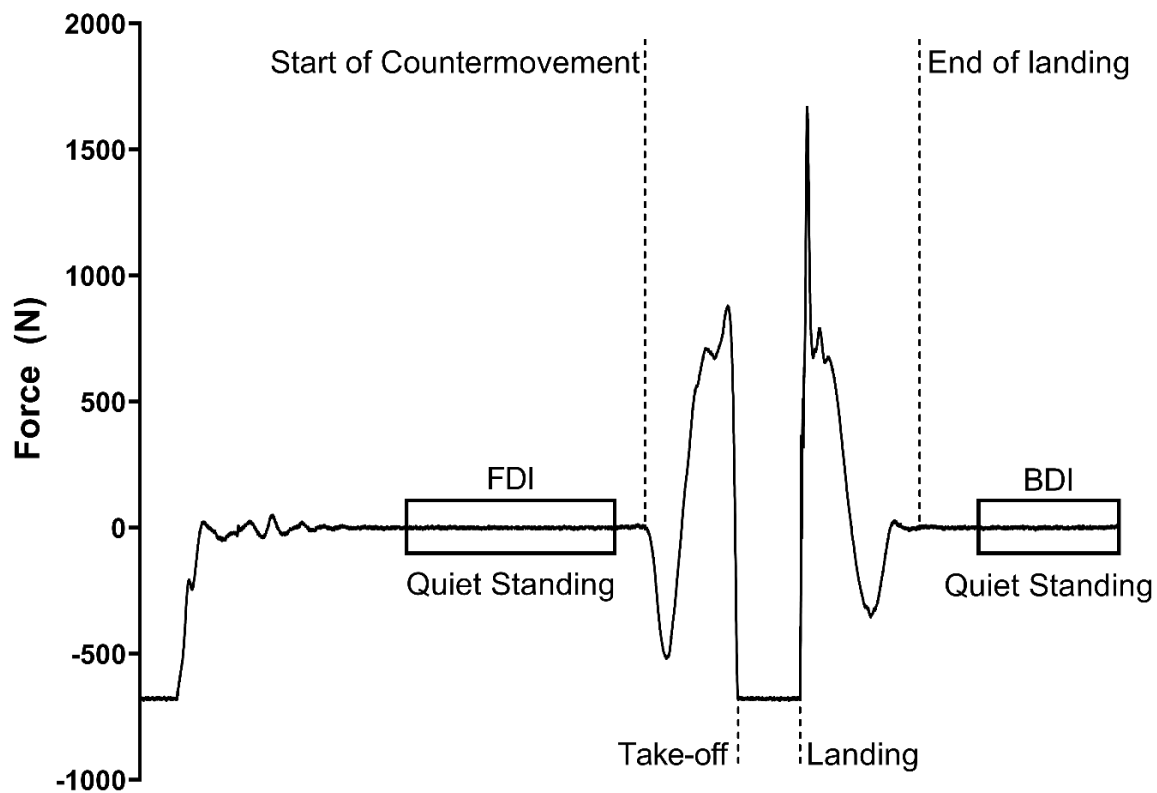


Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of the countermovement, take-off, landing and end of landing.

Statistical Analysis

Statistical analyses were performed in Prism 8 (GraphPad Software Inc, California, USA) and Python 3.7, with sub-maximal and maximal jump height conditions analysed separately. Individual jump heights measured using the **FDI**, **BDI** and the FT+C method were compared to the reference Kinematic method using Bland-Altman analysis²⁸, where the mean bias examined accuracy while the SD of bias and 95% limits of agreement (LoA) examined the variability²⁹. **Pearson coefficient of determination (R^2)**, estimation statistics and **intraclass correlation using the absolute agreement method** were also calculated, including Cohen's *d* effect size with bootstrapped confidence intervals (CI)³⁰. To compare maximal and sub-

277 maximal jumping, leg length and within-participant heel-lift distance and SD were calculated
278 using the FDI method and examined using Bland-Altman analysis alongside Cohen's d effect
279 size and confidence interval. Cohen's d effect sizes were classified as trivial (< 0.2), small (0.2
- 0.5), medium (0.5 - 0.8) and large (> 0.8).

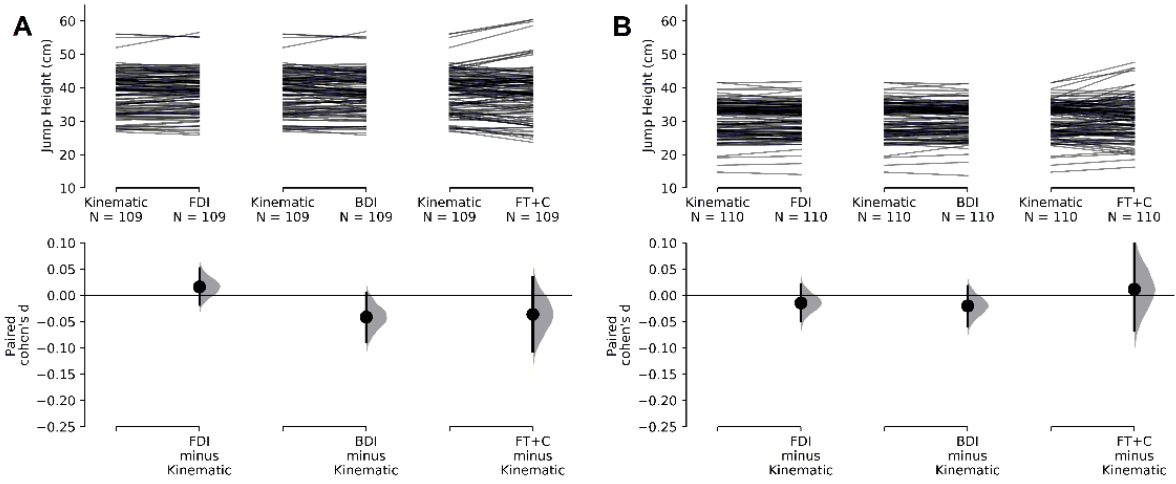
282 Results

283 Bland-Altman bias of BDI landing time was 0.30 ± 0.28 s (95% CI = -0.25 – 0.85 s) longer
284 compared to FDI method push-off time. Bland-Altman bias of, FDI, BDI and FT+C methods
285 during maximal and sub-maximal jumping were within 4 mm of the Kinematic method, which
286 resulted in a trivial effect size (< 0.04). The BDI and FDI methods had the smallest bias and
287 largest ICC for maximal and sub-maximal jumping. However, the FDI method had the smallest
288 SD of bias, LoA and confidence interval, paired with a higher R^2 value for both maximal and
289 sub-maximal jumping. The BDI appears to have a slightly higher variability compare to the
290 FDI method (SD of Bias, 95% LoA), although bias, R^2 value and effect size values were almost
291 identical. The FT+C method was the worst across all measures, with SD of Bias almost double
292 both other methods along with worse 95% LOA, R^2 and ICC scores relative to the FDI and
293 BDI methods (Table 1). However, these differences were small, as Cohen's d effect size
294 confidence interval for all methods in both maximal and sub-maximal jumping overlapped with
295 zero (Figure 2), indicating no statistical difference compared to the kinematic method.

300 *Table 1: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement*
 301 *(LoA), Pearson coefficient of determination, Cohen's d effect size and 95% confidence*
 302 *interval and Intraclass Correlation Coefficient (ICC) and 95% Confidence Interval of the*
 303 *FDI, BDI and FT+C methods compared to the Kinematic method.*

Method	Bias (cm)	SD of Bias (cm)	95% LoA (cm)	R ²	Effect Size & 95% Confidence Interval	ICC & 95% Confidence Interval
Maximal Jumping						
FDI	-0.4	0.9	-2.2 – 1.5	0.989	0.02 (-0.02 – 0.05)	0.994 (0.99 – 1.00)
BDI	-0.1	1.2	-2.3 – 2.2	0.983	-0.04 -0.09 – 0.01	0.995 0.99 – 1.00
FT+C	-0.4	2.3	-4.8 – 4.1	0.9386	-0.04 -0.11 – 0.03	0.954 (0.89 – 0.98)
Sub-maximal Jumping						
FDI	-0.1	0.7	-1.5 – 1.4	0.988	-0.02 -0.05 – 0.02	0.995 (0.99 – 1.00)
BDI	-0.1	0.9	-1.7 – 1.9	0.982	-0.02 0.06 – 0.02	0.996 (0.99 – 1.00)
FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 -0.07 – 0.09	0.927 (0.84 – 0.97)

304
 305 To determine if heel-lift distance changed due to jumping intensity, average within-participant
 306 heel-lift distance and within-participant heel-lift SD were calculated using the FDI method and
 307 compared between maximal and submaximal jumping. Average within-participant heel-lift
 308 distance during sub-maximal jumping decreased by 1.3 ± 1.2 cm (95% LoA = -3.7 – 1.2 cm)
 309 with a large effect size of -0.815 (CI= -1.37 – -0.172) compared to maximal jumping. SD of
 310 average within-participant heel-lift distance during sub-maximal jumping increased by $0.2 \pm$
 311 0.6 cm (95% LoA = -1.0 – 1.4 cm) with a small effect size of 0.416 (CI = -0.205 – 0.955)
 312 compared to maximal jumping. Therefore, average heel-lift distance decreased with sub-
 313 maximal jumping, but variability was only slightly altered. Despite a decrease in heel-lift
 314 distance, the FT+C method accuracy and variability were almost identical during both maximal
 315 and sub-maximal jumping (Table 1). Leg length during landing of sub-maximal jumping was
 316 1.1 ± 2.0 cm (95% LoA = -2.8 – 5.0 cm) greater than maximal jumping.



317 *Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs*
 318 *indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping*
 319 *while graph B presents indicates submaximal jumping.*

321 Discussion

322 These results reinforce the finding from Wank and Coenning²⁰, and also support our first
 323 hypothesis, demonstrating that jump height calculated using the FDI and BDI methods are on
 324 average equivalent and could be used interchangeably, although BDI may have slightly higher
 325 variability compared to the FDI method (Table 1 - SD of Bias and 95% LoA). For both BDI
 326 and FDI methods, Cohen's d effect sizes were classified as trivial and confidence intervals
 327 overlapped with zero, indicating no differences compared to rigid-body kinematic modelling
 328 methods on average (Figure 2).

330 The landing time for the BDI method was on average greater by 0.3 s compared to the push-
 331 off time for the FDI method, and therefore it is possible that the slightly longer time to return
 332 to normal standing during landing may result in greater variability of this method, however the
 333 effect was very small. When examining squat jumping or drop jumping, the BDI method will
 334 likely produce accurate results and only uses a single force plate. **It must be noted that while**

335 landing phases of countermovement jumping, squat jumping and drop jump should be
336 identical, this study only examined countermovement jumping and this ought to be kept in
337 mind when applying these methods to alternative jumping types.

338
339 As expected, jump height calculated by the FDI and BDI methods did not result in any
340 differences between sub-maximal and maximal jumping. The primary aim of examining sub-
341 maximal jumping was to determine if a change in heel-lift distance would influence the
342 accuracy of the FT+C method, which uses an anthropometrically scaled constant to calculate
343 jump height. Heel-lift distance between maximal and sub-maximal jumping was reduced on
344 average by 1.3 ± 1.2 cm (large effect size) paired with a 0.2 ± 0.5 mm increase in SD of bias
345 (small effect size). Therefore, the FT+C method would be expected to overestimate sub-
346 maximal jump height by 1.3 cm on average, although this should be relatively systematic as
347 there was only a small increase in within participant SD (variability). However, FT + C results
348 were almost identical for both maximal and sub-maximal jumping compared to the Kinematic
349 method. This contradicted our second hypothesis and was likely due to landing with the legs
350 in a more extended position (1.1 cm) during sub-maximal jumping compared to maximal
351 jumping, reducing the time spent in the air. As a result, the overestimation of distance travelled
352 in the air when using the FT method^{10, 22} may be reduced during sub-maximal jumping, which
353 in turn counteracts the overestimation in heel-lift constant to calculate sub-maximal jump
354 height accurately and consistently. This further stresses the necessity of adding an
355 anthropometrically scaled heel-lift constant to account for the FT method alone not measuring
356 heel-lift distance. The FT+C method therefore is a strong tool for calculating jump height
357 without a force plate and can provide coaches and researchers with accurate results in the field.
358 However, it should be noted that the FT+C method had worse SD of bias, 95% LoA, R² value
359 and ICC values than FDI and BDI methods. Therefore, if a force plate is available, the FDI or

360 BDI methods should be employed, as both these methods have reduced variability relative to
1
2 361 the FT+C method.

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9 363 **Conclusion**

10
11 364 This study has demonstrated that the BDI method is equivalent to the FDI and should be used
12
13 365 over the FT method in situations where FDI integration cannot be employed. The BDI method
14
15 366 provides coaches and researchers with an additional method to examine jump height and
16
17 367 assuming the same lading pattern between different jump types, enables direct comparisons
18
19 368 between countermovement jumping, drop jumping and squat jumping using a single force
20
21 369 plate. Finally, the FT+C method appears to be able to account for changes in jumping intensity,
22
23 370 further strengthening this methods ability to calculate jump height in the field, although
24
25 371 variability of this method was worse than both BDI and FDI.
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36
37 374 Analysis of Motion, Entertainment Research and Applications, EP/M023281/1
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43 376 **Data Sharing:** Data has not been made available due to this data set being collected as part
44
45 377 of a larger study which will be made publicly available at a later date.
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52 379 **Conflict of Interest:** There are no conflicts of interest.
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465 **Table**

466 Table 2: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement
 467 (LoA), **Pearson** coefficient of determination, Cohen's d effect size and 95% confidence
 468 interval and **Intraclass Correlation Coefficient (ICC)** and **95% Confidence Interval of the**
 469 **FDI, BDI and FT+C methods compared to the Kinematic method.**

Method	Bias (cm)	SD of Bias (cm)	95% LoA (cm)	R²	Effect Size & 95% Confidence Interval	ICC & 95% Confidence Interval
Maximal Jumping						
FDI	-0.4	0.9	-2.2 – 1.5	0.989	0.02 (-0.02 – 0.05)	0.994 (0.99 – 1.00)
BDI	-0.1	1.2	-2.3 – 2.2	0.983	-0.04 (-0.09 – 0.01)	0.995 (0.99 – 1.00)
FT+C	-0.4	2.3	-4.8 – 4.1	0.9386	-0.04 (-0.11 – 0.03)	0.954 (0.89 – 0.98)
Sub-maximal Jumping						
FDI	-0.1	0.7	-1.5 – 1.4	0.988	-0.02 (-0.05 – 0.02)	0.995 (0.99 – 1.00)
BDI	-0.1	0.9	-1.7 – 1.9	0.982	-0.02 (0.06 – 0.02)	0.996 (0.99 – 1.00)
FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 (-0.07 – 0.09)	0.927 (0.84 – 0.97)

472 **Figure Legend**

473 Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of
 474 the countermovement, take-off, landing and end of landing.

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 476 Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs
 477 indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping
 478 while graph B presents indicates submaximal jumping.

1 Backward Double Integration is a Valid Method to Calculate Maximal and Sub-Maximal 2 Jump Height

3

4 **Abstract**

5 The backward double integration method uses one force plate and could calculate jump height
6 for countermovement jumping, squat jumping and drop jumping by analysing the landing phase
7 instead of the push-off phase. **This study compared the accuracy and variability of the forward**
8 **double integration (FDI), backwards double integration (BDI) and Flight Time + Constant**
9 **(FT+C) methods, against the marker-based rigid-body modelling method.** It was hypothesised
10 that jump height calculated with the BDI method would be equivalent to the FDI method, while
11 the FT+C method would have reduced accuracy and increased variability during sub-maximal
12 jumping compared to maximal jumping. Twenty-four volunteers performed five maximal and
13 sub-maximal countermovement jumps, while force plate **and motion capture data** were
14 collected. The BDI method calculated equivalent mean jump heights to the FDI method, **with**
15 **only slightly higher variability (2-3 mm)**, and therefore can be used in situations where FDI
16 cannot be employed. **The FT+C method was able to account for reduced heel-lift distance,**
17 **despite employing an anthropometrically scaled heel-lift constant.** However, across both sub-
18 **maximal and maximal jumping, it had increased variability (1.1 cm) compared to FDI and BDI**
19 **and should not be used when alternate methods are available.**

20

21 **Keywords**

22 Countermovement jump, squat jump, drop jump, force plate, vertical jump, flight time

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26 **Introduction**

27 Jump height is often used to estimate athletic lower limb neuromuscular capabilities during
28 training ^{1, 2} and rehabilitation ³. Additionally, jump height is commonly used to explore
29 foundational human movement, as it requires coordination from multiple joints and can be
30 performed across a range of intensities ^{4,5}. We defined jump height as the distance between the
31 centre of mass (CoM) during standing and the apex of the jump, as this period includes all the
32 work performed to propel the CoM into the air. The measure requires the jumper to break
33 contact with the ground and therefore due to heel-raise commonly lifting the centre of mass 8-
34 10cm ⁶⁻⁹, a jump height below this height is very uncommon. **As such, methods for calculating**
35 **jump height that do not take heel-lift into account will substantially underestimate jump height**
36 **7, 10, 11**. Countermovement jump height is commonly used in power estimation formulas as an
37 estimate of athlete power output^{12, 13}, and the countermovement, squat and drop jump are often
38 compared to examine neuromuscular functional capabilities¹⁴⁻¹⁶. However, comparing jump
39 height between jump types can be difficult as methods for calculating jump height may be
40 influenced by different starting positions^{4, 17}.

41

42 One of the most accessible and reliable jump height calculation methods is the forward double
43 integration (FDI) method, which only requires a single force plate and calculates jump height
44 using the ground reaction force (GRF) trace during push off ¹⁸. The net GRF trace is divided
45 by body mass to calculate CoM acceleration, which is integrated once to calculate CoM
46 velocity and then integrated a second time to calculate CoM displacement at take-off (heel-lift
47 distance). CoM velocity at take-off is input into a projectile motion equation to calculate

48 distance travelled in the air, which is finally summed with the heel-lift distance to calculate
49 jump height. Previous research has demonstrated that using an average body mass for all
50 jumping trials should not be employed, as it can result in jump height errors of up to 4.5 cm ¹⁹.
51 Therefore, the FDI method requires an accurate measure of bodyweight and position of the
52 CoM for every jump, calculated by participants stand as still as possible prior to push-off ¹⁹.
53 Additionally, the period over which FDI is performed needs to be kept as small as possible, so
54 that minute GRF errors do not have time to be exponentially amplified by double integration,
55 which can cause large heel-lift distance errors ¹⁰. Maximal countermovement jumping
56 generally takes about 1 second to perform (end of quiet standing until take-off), which is
57 generally small enough to limit substantial amplification of heel-lift distance errors. However,
58 calculating jump height during squat jumping can result in large heel-lift distance errors, as
59 participants are required to descend and hold the squatted position before performing the jump.
60 The entire jump (end of quiet standing until take-off) can take up to 4-6 seconds and as such,
61 squat jump height should not be calculated using the FDI method ¹⁰. Alternatively, drop
62 jumping requires participants to start on a box next to the force plate and drop down onto it,
63 thus information about participant bodyweight and location of the CoM during quiet standing
64 is missing. This issue can be overcome by placing a second force plate on the drop box or
65 placing the drop box on a force platform to calculate bodyweight and CoM height during quiet
66 standing. If using two force plates, the data from both force plates can then be combined and
67 the FDI method is performed as normal, after which the output is summed with the known
68 height of the drop box to calculate jump height ²⁰. However, this method requires an additional
69 portable force plate to be placed on the drop box, or a single force plate is needed that is large
70 enough to fit both a drop box and space to perform jumping. Due to the errors present when
71 using FDI to measure squat jumping and the additional equipment required to measure jump
72 height during drop jumping, alternative methods are necessary.

73

74 Three-dimensional marker-based motion capture, combined with rigid-body modelling, has
75 commonly been used in laboratories to calculate displacement of the CoM during jumping ²¹.
76 While this method performs strongly at calculating jump height, it has been shown to
77 overestimate flight distance and underestimate heel-lift distance ^{10, 22}, in addition to joint centre
78 location errors that may be up to 30 mm ²³. Furthermore, this method requires a substantial
79 amount of additional equipment, software and complex post-processing of data that is far
80 beyond what may be required for many practical applications of jump height. Wade, Lichtwark
81 and Farris ¹⁰ detailed a hybrid method that combines marker-based motion capture with force
82 plates to calculate jump height without time intensive processing of the data and complex rigid-
83 body modelling. However, due to the additional equipment required for this method, it is
84 primarily limited to application in a laboratory setting.

85

86 A simple and cost-effective alternative is the flight time (FT) method, which only requires the
87 time in the air between take-off and landing to be obtained and can be performed with a single
88 force plate, pressure mat ¹⁸ or even a smartphone ²⁴. It is commonly used in field applications
89 to assess countermovement jumping, drop jumping and squat jumping, as the flight phases of
90 each are identical. However, the FT method is not a true measure of jump height as it does not
91 take heel-lift into account, therefore this method consistently underestimates jump height by
92 approximately 8-10 cm depending on the individual ^{7, 25}. Furthermore, the FT method assumes
93 the position of the CoM is the same at take-off and during landing, which is never the case as
94 the legs adopt a more flexed position during landing to attenuate landing forces ²². Previous
95 research has demonstrated that an anthropometrically scaled constant, based on each
96 participant's foot length, may be used as a substitute for heel-lift distance. The constant is then

97 summed with distance travelled in the air calculated by the FT method to estimate jump height
98 ¹⁰. While the FT plus heel-lift constant (FT+C) method demonstrated a substantial
99 improvement compared to the FT method alone ¹⁰, the heel-lift distance during sub-maximal
100 jumping or between countermovement jumping, squat jumping and drop jumping may be
101 inconsistent due to altered coordination strategies. An alternative method that only uses a single
102 force plate and can calculate jump height from any jump type could facilitate improved
103 accuracy for coaches and researchers examining jumping.

104

105 The backwards double integration (BDI) method calculates jump height using the same method
106 as FDI method, except instead of integrating over the push-off phase, integration is performed
107 over the landing phase ^{20, 26}. Jumping starts and ends in a quiet standing position, therefore all
108 the energy generated to propel the CoM upwards must be attenuated during landing. Using the
109 BDI method, jump height could be calculated for countermovement jumping, squat jumping
110 and drop jumping, as the landing phases of these three jump types are performed exactly the
111 same (i.e. landing that is followed immediately by return to quiet standing). It should be noted
112 that BDI cannot calculate CoM distance travelled in the air or heel-lift distance, as this method
113 is measuring the landing phase, however this does not impede its ability to calculate jump
114 height. Additionally, portable force plates may struggle with this method due very high peak
115 ground reaction forces during landing, which can produce clipping of the forces due to maxing
116 out the force plate. Currently, only one study has examined the accuracy of the BDI method,
117 performing analysis during drop jumping and comparing the BDI method to marker-based
118 kinematic modelling. Using paired t-tests, they found that results between methods were not
119 statistically different and therefore the BDI was a valid method for calculating jump height.
120 However, pairwise testing can only determine if a significant difference exists, not that two
121 methods produce the same results for accuracy and variability. Finally, it is valuable to know

122 if the FDI and BDI methods produce equivalent results and could be used interchangeably,
123 although this can only be tested on countermovement jumping as FDI cannot be used with drop
124 jumping or squat jumping. Therefore, the first aim of this study was to build previous work ²⁰
125 by comparing individual sub-maximal and maximal countermovement jump heights calculated
126 using the FDI, BDI and FT+C methods against marker-based rigid-body kinematic modelling
127 methods, which were not dependent on force plate data and could therefore be used as a
128 reference method. We believe results obtained during countermovement jumping of this study
129 are directly comparable to drop jumping and squat jumping as landing phases in these jumps
130 should be identical. It was hypothesised that the BDI method would demonstrate equivalent
131 accuracy and variability compared to the FDI and the FT+C method would have reduced
132 accuracy compared to the BDI and FDI methods.

133

134 Sub-maximal jump heights are often be used to explore how complex full body movements are
135 executed ^{5, 6}. However, there is potential for increased movement variability during sub-
136 maximal movements and while the **FDI and BDI** method are unlikely to be affected by different
137 jump intensities, the FT+C method uses a participant-specific anthropometrically scaled heel-
138 lift constant that does not change, irrespective of the jumping intensity. Therefore, it is likely
139 that during sub-maximal jumping, heel-lift distance will be decreased and produced with
140 greater variability, which may reduce the accuracy of the FT+C method during sub-maximal
141 jumping. The second aim of this study was to examine if jump height calculated with the FT+C
142 method, as well as the **FDI and BDI**, have reduced accuracy during sub-maximal jumping
143 compared to maximal jumping. It was hypothesised that while the **FDI and BDI** method would
144 not be affected, the FT+C method would overestimate jump height and have greater variability
145 during sub-maximal jumping compared to maximal jumping.

146

147 **Methods**

148 Twenty-three **healthy** participants (11 female and 12 male, age = 28 ± 5 years, mass = 70 ± 12
149 kg, height = 172 ± 9 cm) **without any formal jumping** training gave written informed consent
150 to participate in this study. Ethics was approved by the University of XXXXX, Research Ethics
151 Approval Committee for Health (XXXXXXXXXX). Participants attended the XXXXXXXXXXXX
152 at the XXXXXXXX on a single occasion and performed jumping in their own shoes. After a
153 self-directed warmup, participants completed five sub-maximal countermovement jumps and
154 five maximal countermovement jumps assigned in a block randomised order. During maximal
155 jumping, participants were asked to jump maximally, while during sub-maximal jumping,
156 participants were asked to jump at 50% maximal effort. For each trial, participants started off
157 the force plate while it was zeroed and then stepped onto two force plates (one foot on each
158 plate), where they assumed a quiet standing position with their arms on their hips (no arm swing
159 during jumping). Participants stood still for 2-3 seconds before performing either a sub-
160 maximal or maximal countermovement jump. Upon landing they were told to resume their
161 quiet standing position, at which point data collection was terminated.

162

163 **Motion capture data was recorded using a 15-camera Qualisys motion capture system (Oqus,**
164 **Qualisys, Gothenburg, Sweden) at 200 Hz. A full body marker-set consisting of 44 individual**
165 **markers and eight clusters were attached to participants, with a full description of marker**
166 **locations detailed in ²⁷. GRF data were collected from two in-ground force plates (Kistler**
167 **9287CA, Winterthur, Switzerland) at 1000 Hz. Motion capture data and GRF data were**
168 **collected in Qualisys Track Manager (QTM, Qualisys, Sweden) and then exported to Visual**
169 **3D (C-Motion, Maryland, USA), where rigid-body, six degrees of freedom, kinematic**

170 modelling was performed to calculate displacement of the centre of mass (Kinematic Method).
171 GRF and CoM displacement calculated using rigid-body modelling was imported into Python
172 3.7 where a custom script calculated jump height using the Kinematic Method, FDI method,
173 BDI method and the FT+C method. During data processing, all trials that did not end with the
174 participant standing quietly on the plate were excluded, resulting in 21 of 240 trials being
175 excluded. Thus, for all methods, 109 maximal jumping trials and 110 sub-maximal jumping
176 trials were analysed using pairwise comparison.

177

178 Forward Double Integration (FDI)

179 The vertical GRF traces from each plate were combined and the average GRF during the time
180 in the air was subtracted from the entire GRF trace to digitally zero the force plate. The quiet
181 standing period was identified, and bodyweight was calculated by taking a mean value over
182 one second (Figure 1). Net GRF was then obtained by subtracting bodyweight from the zeroed
183 GRF trace. Following the methods outlined by Vanrenterghem, De Clercq¹⁹, the net GRF trace
184 and the same period that bodyweight was calculated over were used to identify, net GRF
185 maximum, minimum and standard deviation (SD). To identify start of the countermovement
186 after quiet standing, the first value that exceeded either the maximum + one SD or the minimum
187 – one SD was identified. Working backwards, the first value that exceeded 0 N (either positive
188 or negative) was identified as the start of the countermovement (Figure 1)¹⁹. Take-off was
189 identified as the first point the net GRF trace exceeded negative bodyweight following push-
190 off (Figure 1). To calculate jump height, the net GRF trace was divided by body mass
191 (bodyweight/gravity) to calculate CoM acceleration. The CoM acceleration trace was
192 integrated (trapezoidal) to calculate CoM velocity which was then subsequently integrated to
193 calculate CoM displacement at take-off (heel-lift). The final value of the CoM velocity trace
194 was used to calculate distance travelled in the air using the projectile motion equation:

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$$v^2 = u^2 + 2as$$

Where v equals the velocity at take-off, u equals the velocity at the apex of the jump (0 m/s), a equals gravity (9.81 m/s²) and s equals the distance travelled in the air. The distance travelled in the air and heel-lift distance were then summed to calculate jump height. Within-participant heel-lift averages and SD's were calculated by taking the mean value of the heel-lift distance or SD for each individual participant, within each jump condition (sub-maximal and maximal).

Backwards Double Integration (BDI)

Using the same initial protocol as FDI, vertical GRF and the zeroed GRF trace were calculated. Bodyweight was calculated by starting from the last data point and moving backwards to identify the quiet standing period immediately after landing (0.5 seconds of quiet standing) at which point the GRF trace was averaged (Figure 1). Net GRF was calculated by subtracting bodyweight from the zeroed GRF and then net GRF maximum, minimum and SD values during quiet standing were identified. Working backwards from the end of the trial, the first value that exceeded the maximum + one SD or the minimum - one SD was obtained. Then moving forward, the last point that exceeded 0 N (positive or negative) was identified as the end of the landing phase (i.e. quiet standing, Figure 1). Start of landing was identified as first value to exceed negative bodyweight after push-off (Figure 1). The net GRF trace was trimmed from the start of landing to the end of landing and then reversed so that sequentially, end of landing occurred before start of landing. From this point, the FDI method was repeated by calculating CoM acceleration, performing double integration of the CoM acceleration trace, calculating distance travelled in the air using projectile motion and summed this value with CoM displacement at landing to calculate jump height.

219 Kinematic Rigid-Body Modelling

220 Displacement of the CoM calculated in Visual3D was imported into Python 3.7. Standing
221 height was calculated as the average height of the CoM for 300 ms prior to the start of push-
222 off, using event timing calculated by the FDI method. Maximal height of the CoM was then
223 obtained (apex of the jump) and the average standing height was subtracted from the maximal
224 CoM height to calculate jump height. Leg length comparison between sub-maximal and
225 maximal jumping was performed by calculating the vertical position of the centre of mass of
226 the pelvis at landing. The average vertical position between the distal ends of the right and left
227 foot were then calculated and subtracted from the pelvis COM position to calculate leg length.

228

229 Flight Time + Constant (FT+C)

230 The FT method calculated the CoM distance travelled in the air by using take-off (FDI) and
231 landing events (BDI) calculated previously. Time in the air was halved and then input into the
232 projectile motion equation:

234
$$s = ut + \frac{1}{2}at^2$$

233

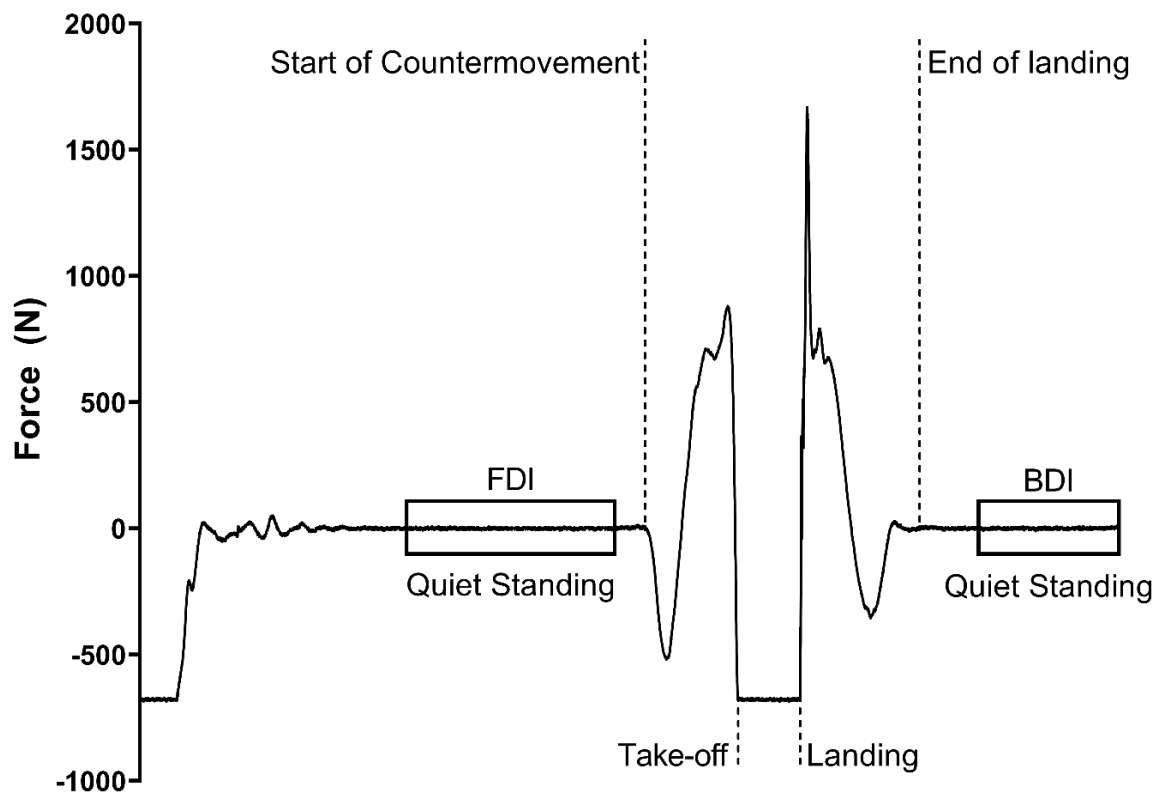
235 Where s equals the distance travelled in the air, u equals the velocity at the apex of the jump (0
236 m/s), a equal's gravity (9.81 m/s²) and t equals half the time in the air. Heel-lift constant was
237 calculated by taking foot measurements using a tape measure which were input in to the
238 formula created by Wade, Lichtwark and Farris ¹⁰

239
$$\text{Constant} = (0.88 \times \text{Foot Length}) + \text{Sole Thickness} - \text{Ankle Height}$$

240 Where *Foot Length* equals the distance between the medial malleoli and the tip of the shoe,
241 *Sole Thickness* equals the thickness of the sole inferior to the 1st phalangeal joint and *Ankle*

242 *Height* equals the distance between the medial malleoli and the ground. All measurements were
243 taken immediately after performing jumping and participants kept their shoes on. Distance
244 travelled in the air for each trial was then summed with each participant's anthropometrically
245 scaled heel-lift constant to calculate jump height.

246



247

248 *Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of*
249 *the countermovement, take-off, landing and end of landing.*

250

251 **Statistical Analysis**

252 Statistical analyses were performed in Prism 8 (GraphPad Software Inc, California, USA) and
253 Python 3.7, with sub-maximal and maximal jump height conditions analysed separately.
254 Individual jump heights measured using the **FDI**, **BDI** and the FT+C method were compared
255 to the reference Kinematic method using Bland-Altman analysis ²⁸, where the mean bias

256 examined accuracy while the SD of bias and 95% limits of agreement (LoA) examined the
257 variability ²⁹. **Pearson coefficient of determination (R^2)**, estimation statistics and **intraclass**
258 **correlation using the absolute agreement method** were also calculated, including Cohen's *d*
259 effect size with bootstrapped confidence intervals (CI) ³⁰. To compare maximal and sub-
260 maximal jumping, **leg length** and within-participant heel-lift distance and SD were calculated
261 using the FDI method and examined using Bland-Altman analysis alongside Cohen's *d* effect
262 size and confidence interval. Cohen's *d* effect sizes were classified as trivial (< 0.2), small (0.2
263 - 0.5), medium (0.5 - 0.8) and large (> 0.8).

264

265 **Results**

266 Bland-Altman bias of BDI landing time was 0.30 ± 0.28 s (95% CI = -0.25 – 0.85 s) longer
267 compared to FDI method push-off time. Bland-Altman bias of, **FDI**, BDI and FT+C methods
268 during maximal and sub-maximal jumping were within **4 mm of the Kinematic** method, which
269 resulted in a trivial effect size (< 0.04). **The BDI and FDI methods had the smallest bias and**
270 **largest ICC for maximal and sub-maximal jumping. However, the FDI method had the smallest**
271 **SD of bias, LoA and confidence interval, paired with a higher R^2 value for both maximal and**
272 **sub-maximal jumping. The BDI appears to have a slightly higher variability compare to the**
273 **FDI method (SD of Bias, 95% LoA), although bias, R^2 value and effect size values were almost**
274 **identical. The FT+C method was the worst across all measures, with SD of Bias almost double**
275 **both other methods along with worse 95% LOA, R^2 and ICC scores relative to the FDI and**
276 **BDI methods (Table 1). However, these differences were small, as Cohen's *d* effect size**
277 **confidence interval for all methods in both maximal and sub-maximal jumping overlapped with**
278 **zero (Figure 2), indicating no statistical difference compared to the kinematic method.**

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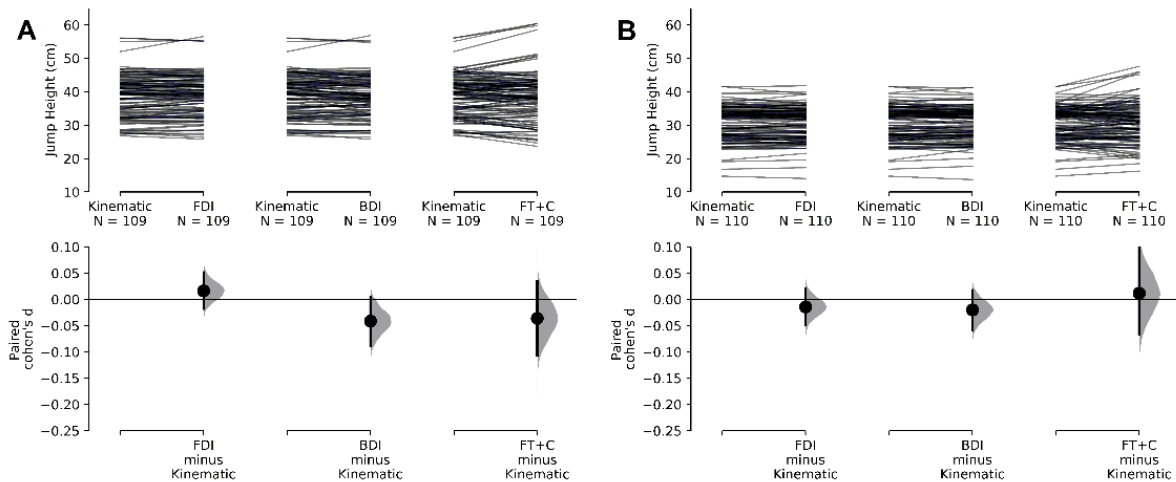
283 *Table 1: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement*
 284 *(LoA), Pearson coefficient of determination, Cohen's d effect size and 95% confidence*
 285 *interval and Intraclass Correlation Coefficient (ICC) and 95% Confidence Interval of the*
 286 *FDI, BDI and FT+C methods compared to the Kinematic method.*

Method	Bias (cm)	SD of Bias (cm)	95% LoA (cm)	R ²	Effect Size & 95% Confidence Interval	ICC & 95% Confidence Interval
Maximal Jumping						
FDI	-0.4	0.9	-2.2 – 1.5	0.989	0.02 (-0.02 – 0.05)	0.994 (0.99 – 1.00)
BDI	-0.1	1.2	-2.3 – 2.2	0.983	-0.04 -0.09 – 0.01	0.995 0.99 – 1.00
FT+C	-0.4	2.3	-4.8 – 4.1	0.9386	-0.04 -0.11 – 0.03	0.954 (0.89 – 0.98)
Sub-maximal Jumping						
FDI	-0.1	0.7	-1.5 – 1.4	0.988	-0.02 -0.05 – 0.02	0.995 (0.99 – 1.00)
BDI	-0.1	0.9	-1.7 – 1.9	0.982	-0.02 0.06 – 0.02	0.996 (0.99 – 1.00)
FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 -0.07 – 0.09	0.927 (0.84 – 0.97)

287

288 To determine if heel-lift distance changed due to jumping intensity, average within-participant
 289 heel-lift distance and within-participant heel-lift SD were calculated using the FDI method and
 290 compared between maximal and submaximal jumping. Average within-participant heel-lift
 291 distance during sub-maximal jumping decreased by 1.3 ± 1.2 cm (95% LoA = -3.7 – 1.2 cm)
 292 with a large effect size of -0.815 (CI= -1.37 – -0.172) compared to maximal jumping. SD of
 293 average within-participant heel-lift distance during sub-maximal jumping increased by $0.2 \pm$
 294 0.6 cm (95% LoA = -1.0 – 1.4 cm) with a small effect size of 0.416 (CI = -0.205 – 0.955)
 295 compared to maximal jumping. Therefore, average heel-lift distance decreased with sub-
 296 maximal jumping, but variability was only slightly altered. Despite a decrease in heel-lift

297 distance, the FT+C method accuracy and variability were almost identical during both maximal
 298 and sub-maximal jumping (Table 1). Leg length during landing of sub-maximal jumping was
 299 1.1 ± 2.0 cm (95% LoA = -2.8 – 5.0 cm) greater than maximal jumping.



300 *Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs*
 301 *indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping*
 302 *while graph B presents indicates submaximal jumping.*

303

304 Discussion

305 These results reinforce the finding from Wank and Coenning²⁰, and also support our first
 306 hypothesis, demonstrating that jump height calculated using the FDI and BDI methods are on
 307 average equivalent and could be used interchangeably, although BDI may have slightly higher
 308 variability compared to the FDI method (Table 1 - SD of Bias and 95% LoA). For both BDI
 309 and FDI methods, Cohen's d effect sizes were classified as trivial and confidence intervals
 310 overlapped with zero, indicating no differences compared to rigid-body kinematic modelling
 311 methods on average (Figure 2).

312

313 The landing time for the BDI method was on average greater by 0.3 s compared to the push-
 314 off time for the FDI method, and therefore it is possible that the slightly longer time to return

315 to normal standing during landing may result in greater variability of this method, however the
316 effect was very small. When examining squat jumping or drop jumping, the BDI method will
317 likely produce accurate results and only uses a single force plate. **It must be noted that while**
318 **landing phases of countermovement jumping, squat jumping and drop jump should be**
319 **identical, this study only examined countermovement jumping and this ought to be kept in**
320 **mind when applying these methods to alternative jumping types.**

321

322 **As expected, jump height calculated by the FDI and BDI methods did not result in any**
323 **differences between sub-maximal and maximal jumping. The primary aim of examining sub-**
324 **maximal jumping was to determine if a change in heel-lift distance would influence the**
325 **accuracy of the FT+C method, which uses an anthropometrically scaled constant to calculate**
326 **jump height.** Heel-lift distance between maximal and sub-maximal jumping was reduced on
327 average by 1.3 ± 1.2 cm (large effect size) paired with a 0.2 ± 0.5 mm increase in SD of bias
328 (small effect size). Therefore, the FT+C method would be expected to overestimate sub-
329 maximal jump height by 1.3 cm on average, although this should be relatively systematic as
330 there was only a small increase in within participant SD (variability). However, FT + C results
331 were almost identical for both maximal and sub-maximal jumping compared to the Kinematic
332 method. This contradicted our second hypothesis and **was likely due to landing with the legs**
333 **in a more extended position (1.1 cm) during sub-maximal jumping compared to maximal**
334 **jumping, reducing the time spent in the air.** As a result, the overestimation of distance travelled
335 in the air when using the FT method^{10, 22} may be reduced during sub-maximal jumping, which
336 in turn counteracts the overestimation in heel-lift constant to calculate sub-maximal jump
337 height accurately and consistently. This further stresses the necessity of adding an
338 anthropometrically scaled heel-lift constant to account for the FT method alone not measuring
339 heel-lift distance. The FT+C method therefore is a strong tool for calculating jump height

340 without a force plate and can provide coaches and researchers with accurate results in the field.
341 However, it should be noted that the FT+C method had worse SD of bias, 95% LoA, R² value
342 and ICC values than FDI and BDI methods. Therefore, if a force plate is available, the FDI or
343 BDI methods should be employed, as both these methods have reduced variability relative to
344 the FT+C method.

345

346 **Conclusion**

347 This study has demonstrated that the BDI method is equivalent to the FDI and should be used
348 over the FT method in situations where FDI integration cannot be employed. The BDI method
349 provides coaches and researchers with an additional method to examine jump height and
350 assuming the same lading pattern between different jump types, enables direct comparisons
351 between countermovement jumping, drop jumping and squat jumping using a single force
352 plate. Finally, the FT+C method appears to be able to account for changes in jumping intensity,
353 further strengthening this methods ability to calculate jump height in the field, although
354 variability of this method was worse than both BDI and FDI.

355

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432

433 Table

434 Table 2: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement
435 (LoA), **Pearson** coefficient of determination, Cohen's d effect size and 95% confidence
436 interval and **Intraclass Correlation Coefficient (ICC) and 95% Confidence Interval of the**
437 **FDI, BDI and FT+C methods compared to the Kinematic method.**

Method	Bias (cm)	SD of Bias (cm)	95% LoA (cm)	R ²	Effect Size & 95% Confidence Interval	ICC & 95% Confidence Interval
Maximal Jumping						
FDI	-0.4	0.9	-2.2 – 1.5	0.989	0.02 (-0.02 – 0.05)	0.994 (0.99 – 1.00)
BDI	-0.1	1.2	-2.3 – 2.2	0.983	-0.04 -0.09 – 0.01	0.995 0.99 – 1.00
FT+C	-0.4	2.3	-4.8 – 4.1	0.9386	-0.04 -0.11 – 0.03	0.954 (0.89 – 0.98)
Sub-maximal Jumping						
FDI	-0.1	0.7	-1.5 – 1.4	0.988	-0.02 -0.05 – 0.02	0.995 (0.99 – 1.00)
BDI	-0.1	0.9	-1.7 – 1.9	0.982	-0.02 0.06 – 0.02	0.996 (0.99 – 1.00)
FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 -0.07 – 0.09	0.927 (0.84 – 0.97)

438

439

440 Figure Legend

441 Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of
442 the countermovement, take-off, landing and end of landing.

443

444 Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs
445 indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping
446 while graph B presents indicates submaximal jumping.

Figure 2

