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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:	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.
Order of Authors:	Logan Wade
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Response to Reviewers:	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. 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. 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

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 9. 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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Backward Double Integration is a Valid Method to Calculate Maximal and Sub-Maximal Jump Height

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Abstract

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

Keywords

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

Introduction

Jump height is often used to estimate athletic lower limb neuromuscular capabilities during training [1, 2] and rehabilitation [3]. Additionally, jump height is commonly used to explore foundational human movement, as it requires coordination from multiple joints and can be performed across a range of intensities [4, 5]. We defined jump height as the distance between the centre of mass (CoM) during standing and the apex of the jump, as this period includes all the work performed to propel the CoM into the air. The measure requires the jumper to break contact with the ground and therefore due to heel-raise commonly lifting the centre of mass 8-10cm [6-9], a jump height below this height is very uncommon. As such, methods for calculating jump height that do not take heel-lift into account will substantially underestimate jump height [7, 10, 11]. Countermovement jump height is commonly used in power estimation formulas as an estimate of athlete power output[12, 13], and the countermovement, squat and drop jump are often compared to examine neuromuscular functional capabilities[14-16]. However, comparing jump height between jump types can be difficult as methods for calculating jump height may be influenced by different starting positions[4, 17].

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

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

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

While this method performs strongly at calculating jump height, it has been shown to overestimate flight distance and underestimate heel-lift distance [10, 22], in addition to joint centre location errors that may be up to 30 mm [23]. Furthermore, this method requires a substantial amount of additional equipment, software and complex post-processing of data that is far beyond what may be required for many practical applications of jump height. Wade, Lichtwark and Farris [10] detailed a hybrid method that combines marker-based motion capture with force plates to calculate jump height without time intensive processing of the data and complex rigid-body modelling. However, due to the additional equipment required for this method, it is primarily limited to application in a laboratory setting.

A simple and cost-effective alternative is the flight time (FT) method, which only requires the time in the air between take-off and landing to be obtained and can be performed with a single force plate, pressure mat [18] or even a smartphone [24]. It is commonly used in field applications to assess countermovement jumping, drop jumping and squat jumping, as the flight phases of each are identical. However, the FT method is not a true measure of jump height as it does not take heel-lift into account, therefore this method consistently underestimates jump height by approximately 8-10 cm depending on the individual [7, 25]. Furthermore, the FT method assumes the position of the CoM is the same at take-off and during landing, which is never the case as the legs adopt a more flexed position during landing to attenuate landing forces [22]. Previous research has demonstrated that an anthropometrically scaled constant, based on each participant’s foot length, may be used as a substitute for heel-lift distance. The constant is then summed with distance travelled in the air calculated by the FT method to estimate jump height [10]. While the FT plus heel-lift constant (FT+C) method demonstrated a substantial improvement compared to the FT method alone [10], the heel-lift distance during sub-maximal jumping or between countermovement jumping, squat jumping and drop jumping may be inconsistent due to altered coordination strategies. An alternative method that only uses a single force plate and can calculate jump height from any jump type could facilitate improved accuracy for coaches and researchers examining jumping.

The backwards double integration (BDI) method calculates jump height using the same method as FDI method, except instead of integrating over the push-off phase, integration is performed over the landing phase [20, 26]. Jumping starts and ends in a quiet standing position, therefore all the energy generated to propel the CoM upwards must be attenuated during landing. Using the BDI method, jump height could be calculated for countermovement jumping, squat jumping and drop jumping, as the landing phases of these three jump types are performed exactly the same (i.e. landing that is followed immediately by return to quiet standing). It should be noted that BDI cannot calculate CoM distance travelled in the air or heel-lift distance, as this method is measuring the landing phase, however this does not impede its ability to calculate jump height. Additionally, portable force plates may struggle with this method due very high peak ground reaction forces during landing, which can produce clipping of the forces due to maxing out the force plate. Currently, only one study has examined the accuracy of the BDI method, performing analysis during drop jumping and comparing 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. However, pairwise testing can only determine if a significant difference exists, not that two methods produce the same results for accuracy and variability. 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 [20] 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.

Sub-maximal jump heights are often be used to explore how complex full body movements are executed [5, 6]. 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.

Methods

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

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 [27]. GRF data were collected from two in-ground force plates (Kistler 9287CA, Winterthur, Switzerland) at 1000 Hz. Motion capture data and GRF data were collected in Qualisys Track Manager (QTM, Qualisys, Sweden) and then exported to 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. During data processing, all trials that did not end with the participant standing quietly on the plate were excluded, resulting in 21 of 240 trials being excluded. Thus, for all methods, 109 maximal jumping trials and 110 sub-maximal jumping trials were analysed using pairwise comparison.

Forward Double Integration (FDI)

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

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

Where v equals the velocity at take-off, u equals the velocity at the apex of the jump (0 m/s), a equal's gravity (9.81 m/s^2) 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.

Kinematic Rigid-Body Modelling

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

Flight Time + Constant (FT+C)

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

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

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

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

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

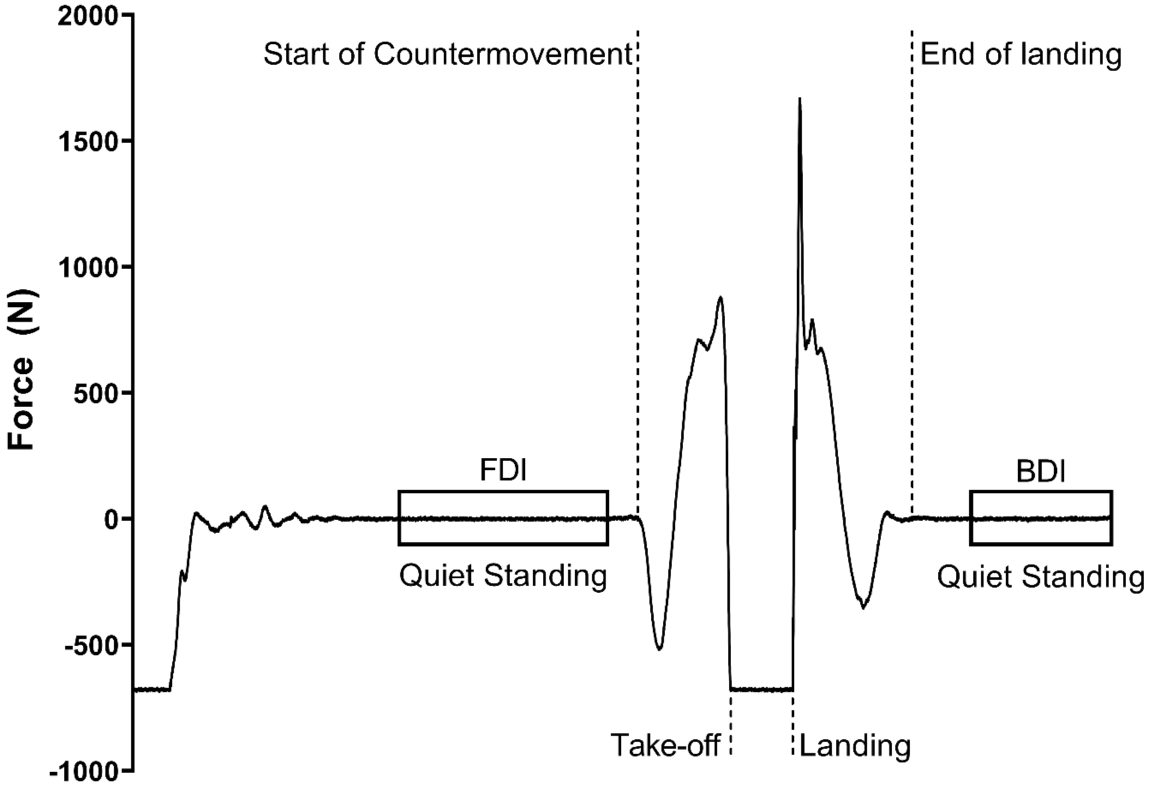

Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of the countermovement, take-off, landing and end of landing.

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 analysis [28], where the mean bias examined accuracy while the SD of bias and 95% limits of agreement (LoA) examined the variability [29]. 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-maximal jumping, leg length and within-participant heel-lift distance and SD were calculated using the FDI method and examined using Bland-Altman analysis alongside Cohen's d effect 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).

Results

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

Table 1: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement (LoA), Pearson coefficient of determination, Cohen's d effect size and 95% confidence interval and Intraclass Correlation Coefficient (ICC) and 95% Confidence Interval of the 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)

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

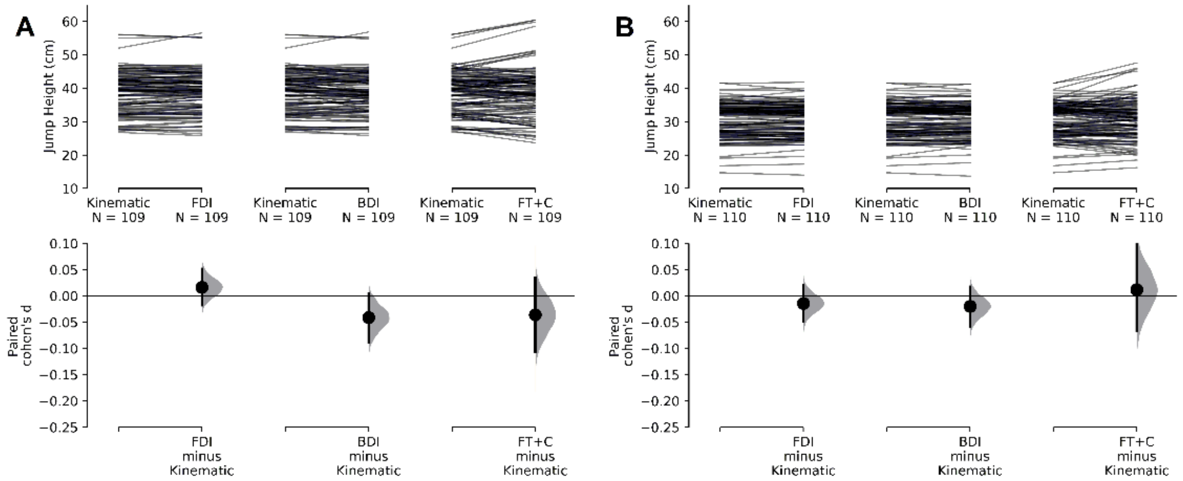

Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping while graph B presents indicates submaximal jumping.

Discussion

These results reinforce the finding from Wank and Coenning [20], 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).

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. When examining squat jumping or drop jumping, the BDI method will likely produce accurate results and only uses a single force plate. 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.

As expected, jump height calculated by the FDI and BDI methods did not result in any differences between sub-maximal and maximal jumping. The primary aim of examining sub-maximal jumping was to determine if a change in heel-lift distance would influence the accuracy of the FT+C method, which uses an anthropometrically scaled constant to calculate jump height. Heel-lift distance between maximal and sub-maximal jumping was reduced on average by 1.3 ± 1.2 cm (large effect size) paired with a 0.2 ± 0.5 mm increase in SD of bias (small effect size). Therefore, the FT+C method would be expected to overestimate sub-maximal jump height by 1.3 cm on average, although this should be relatively systematic as there was only a small increase in within participant SD (variability). However, FT + C results were almost identical for both maximal and sub-maximal jumping compared to the Kinematic method. This contradicted our second hypothesis and was likely due to landing with the legs in a more extended position (1.1 cm) during sub-maximal jumping compared to maximal jumping, reducing the time spent in the air. As a result, the overestimation of distance travelled in the air when using the FT method [10, 22] may be reduced during sub-maximal jumping, which in turn counteracts the overestimation in heel-lift constant to calculate sub-maximal jump height accurately and consistently. This further stresses the necessity of adding an anthropometrically scaled heel-lift constant to account for the FT method alone not measuring heel-lift distance. The FT+C method therefore is a strong tool for calculating jump height without a force plate and can provide coaches and researchers with accurate results in the field. However, it should be noted that the FT+C method had worse SD of bias, 95% LoA, R^2 value and ICC values than FDI and BDI methods. Therefore, if a force plate is available, the FDI or

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

Conclusion

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

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Data Sharing: Data has not been made available due to this data set being collected as part of a larger study which will be made publicly available at a later date.

Conflict of Interest: There are no conflicts of interest.

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Table

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

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FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 -0.07 – 0.09	0.927 (0.84 – 0.97)

Figure Legend

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.

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

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

Abstract

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

Keywords

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

Introduction

Jump height is often used to estimate athletic lower limb neuromuscular capabilities during training [1, 2] and rehabilitation [3]. Additionally, jump height is commonly used to explore foundational human movement, as it requires coordination from multiple joints and can be performed across a range of intensities [4, 5]. We defined jump height as the distance between the centre of mass (CoM) during standing and the apex of the jump, as this period includes all the work performed to propel the CoM into the air. The measure requires the jumper to break contact with the ground and therefore due to heel-raise commonly lifting the centre of mass 8-10cm [6-9], a jump height below this height is very uncommon. As such, methods for calculating jump height that do not take heel-lift into account will substantially underestimate jump height [7, 10, 11]. Countermovement jump height is commonly used in power estimation formulas as an estimate of athlete power output[12, 13], and the countermovement, squat and drop jump are often compared to examine neuromuscular functional capabilities[14-16]. However, comparing jump height between jump types can be difficult as methods for calculating jump height may be influenced by different starting positions[4, 17].

One of the most accessible and reliable jump height calculation methods is the forward double integration (FDI) method, which only requires a single force plate and calculates jump height using the ground reaction force (GRF) trace during push off [18]. The net GRF trace is divided by body mass to calculate CoM acceleration, which is integrated once to calculate CoM velocity and then integrated a second time to calculate CoM displacement at take-off (heel-lift distance). CoM velocity at take-off is input into a projectile motion equation to calculate distance travelled in the air, which is finally summed with the heel-lift distance to calculate jump height. Previous research has demonstrated that using an average body mass for all jumping trials should not be employed, as it can result in jump height errors of up to 4.5 cm [19]. Therefore, the FDI method requires an accurate measure of bodyweight and position of the CoM for every jump, calculated by participants stand as still as possible prior to push-off [19]. Additionally, the period over which FDI is performed needs to be kept as small as possible, so that minute GRF errors do not have time to be exponentially amplified by double integration, which can cause large heel-lift distance errors [10]. Maximal countermovement jumping generally takes about 1 second to perform (end of quiet standing until take-off), which is generally small enough to limit substantial amplification of heel-lift distance errors. However, calculating jump height during squat jumping can result in large heel-lift distance errors, as participants are required to descend and hold the squatted position before performing the jump. The entire jump (end of quiet standing until take-off) can take up to 4-6 seconds and as such, squat jump height should not be calculated using the FDI method [10]. Alternatively, drop jumping requires participants to start on a box next to the force plate and drop down onto it, thus information about participant bodyweight and location of the CoM during quiet standing is missing. This issue can be overcome by placing a second force plate on the drop box or placing the drop box on a force platform to calculate bodyweight and CoM height during quiet standing. If using two force plates, the data from both force plates can then be combined and the FDI method is performed as normal, after which the output is summed with the known height of the drop box to calculate jump height [20]. However, this method requires an additional portable force plate to be placed on the drop box, or a single force plate is needed that is large enough to fit both a drop box and space to perform jumping. Due to the errors present when using FDI to measure squat jumping and the additional equipment required to measure jump height during drop jumping, alternative methods are necessary.

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

A simple and cost-effective alternative is the flight time (FT) method, which only requires the time in the air between take-off and landing to be obtained and can be performed with a single force plate, pressure mat [18] or even a smartphone [24]. It is commonly used in field applications to assess countermovement jumping, drop jumping and squat jumping, as the flight phases of each are identical. However, the FT method is not a true measure of jump height as it does not take heel-lift into account, therefore this method consistently underestimates jump height by approximately 8-10 cm depending on the individual [7, 25]. Furthermore, the FT method assumes the position of the CoM is the same at take-off and during landing, which is never the case as the legs adopt a more flexed position during landing to attenuate landing forces [22]. Previous research has demonstrated that an anthropometrically scaled constant, based on each participant’s foot length, may be used as a substitute for heel-lift distance. The constant is then summed with distance travelled in the air calculated by the FT method to estimate jump height [10]. While the FT plus heel-lift constant (FT+C) method demonstrated a substantial improvement compared to the FT method alone [10], the heel-lift distance during sub-maximal jumping or between countermovement jumping, squat jumping and drop jumping may be inconsistent due to altered coordination strategies. An alternative method that only uses a single force plate and can calculate jump height from any jump type could facilitate improved accuracy for coaches and researchers examining jumping.

The backwards double integration (BDI) method calculates jump height using the same method as FDI method, except instead of integrating over the push-off phase, integration is performed over the landing phase [20, 26]. Jumping starts and ends in a quiet standing position, therefore all the energy generated to propel the CoM upwards must be attenuated during landing. Using the BDI method, jump height could be calculated for countermovement jumping, squat jumping and drop jumping, as the landing phases of these three jump types are performed exactly the same (i.e. landing that is followed immediately by return to quiet standing). It should be noted that BDI cannot calculate CoM distance travelled in the air or heel-lift distance, as this method is measuring the landing phase, however this does not impede its ability to calculate jump height. Additionally, portable force plates may struggle with this method due very high peak ground reaction forces during landing, which can produce clipping of the forces due to maxing out the force plate. Currently, only one study has examined the accuracy of the BDI method, performing analysis during drop jumping and comparing 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. However, pairwise testing can only determine if a significant difference exists, not that two methods produce the same results for accuracy and variability. 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 [20] 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.

Sub-maximal jump heights are often be used to explore how complex full body movements are executed [5, 6]. 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.

Methods

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. Ethics was approved by the University of XXXXX, Research Ethics Approval Committee for Health (XXXXXXXX). Participants attended the XXXXXXXXXX at the XXXXXXX on a single occasion and performed jumping in their own shoes. After a self-directed warmup, participants completed five sub-maximal countermovement jumps and five maximal countermovement jumps assigned in a block randomised order. During maximal jumping, participants were asked to jump maximally, while during sub-maximal jumping, participants were asked to jump at 50% maximal effort. For each trial, participants started off the force plate while it was zeroed and then stepped onto two force plates (one foot on each plate), where they assumed a quiet standing position with their arms on their hips (no arm swing during jumping). Participants stood still for 2-3 seconds before performing either a sub-maximal or maximal countermovement jump. Upon landing they were told to resume their quiet standing position, at which point data collection was terminated.

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 [27]. GRF data were collected from two in-ground force plates (Kistler 9287CA, Winterthur, Switzerland) at 1000 Hz. Motion capture data and GRF data were collected in Qualisys Track Manager (QTM, Qualisys, Sweden) and then exported to 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. During data processing, all trials that did not end with the participant standing quietly on the plate were excluded, resulting in 21 of 240 trials being excluded. Thus, for all methods, 109 maximal jumping trials and 110 sub-maximal jumping trials were analysed using pairwise comparison.

Forward Double Integration (FDI)

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

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

Where v equals the velocity at take-off, u equals the velocity at the apex of the jump (0 m/s), a equal's gravity (9.81 m/s^2) 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.

Kinematic Rigid-Body Modelling

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

Flight Time + Constant (FT+C)

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

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

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

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

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

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

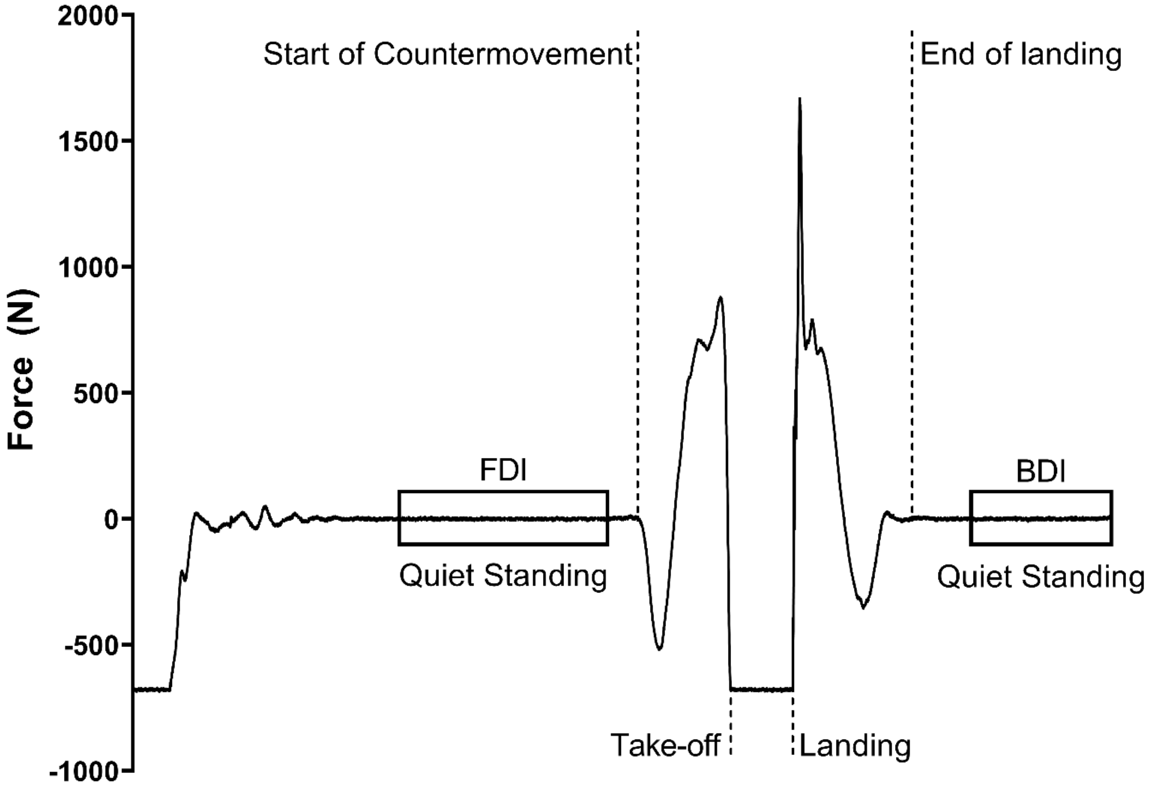

Figure 1: Example net GRF trace of one trial with event detections for quiet standing, start of the countermovement, take-off, landing and end of landing.

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 analysis [28], where the mean bias examined accuracy while the SD of bias and 95% limits of agreement (LoA) examined the variability [29]. 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-maximal jumping, leg length and within-participant heel-lift distance and SD were calculated using the FDI method and examined using Bland-Altman analysis alongside Cohen's d effect 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).

Results

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

Table 1: Bland-Altman analysis bias, standard deviation (SD) of bias, limits of agreement (LoA), Pearson coefficient of determination, Cohen's d effect size and 95% confidence interval and Intraclass Correlation Coefficient (ICC) and 95% Confidence Interval of the 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)

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

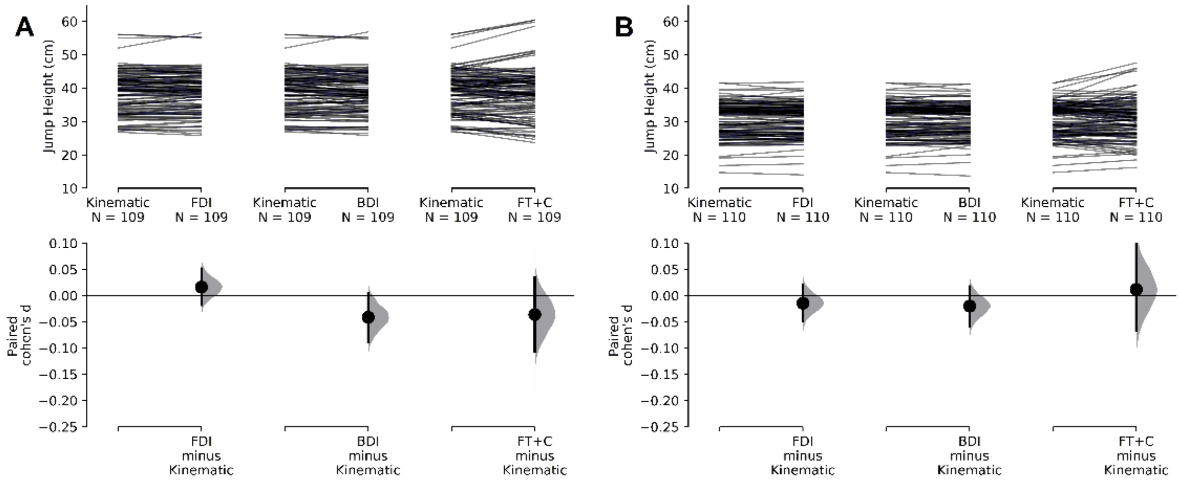

Figure 2: Raw pairwise data of BDI and FT+C compared to the FDI method. Lower graphs indicate Cohen's d effect sizes and confidence intervals. Graph A presents maximal jumping while graph B presents indicates submaximal jumping.

Discussion

These results reinforce the finding from Wank and Coenning [20], 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).

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. When examining squat jumping or drop jumping, the BDI method will likely produce accurate results and only uses a single force plate. 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.

As expected, jump height calculated by the FDI and BDI methods did not result in any differences between sub-maximal and maximal jumping. The primary aim of examining sub-maximal jumping was to determine if a change in heel-lift distance would influence the accuracy of the FT+C method, which uses an anthropometrically scaled constant to calculate jump height. Heel-lift distance between maximal and sub-maximal jumping was reduced on average by 1.3 ± 1.2 cm (large effect size) paired with a 0.2 ± 0.5 mm increase in SD of bias (small effect size). Therefore, the FT+C method would be expected to overestimate sub-maximal jump height by 1.3 cm on average, although this should be relatively systematic as there was only a small increase in within participant SD (variability). However, FT + C results were almost identical for both maximal and sub-maximal jumping compared to the Kinematic method. This contradicted our second hypothesis and was likely due to landing with the legs in a more extended position (1.1 cm) during sub-maximal jumping compared to maximal jumping, reducing the time spent in the air. As a result, the overestimation of distance travelled in the air when using the FT method [10, 22] may be reduced during sub-maximal jumping, which in turn counteracts the overestimation in heel-lift constant to calculate sub-maximal jump height accurately and consistently. This further stresses the necessity of adding an anthropometrically scaled heel-lift constant to account for the FT method alone not measuring heel-lift distance. The FT+C method therefore is a strong tool for calculating jump height without a force plate and can provide coaches and researchers with accurate results in the field. However, it should be noted that the FT+C method had worse SD of bias, 95% LoA, R^2 value and ICC values than FDI and BDI methods. Therefore, if a force plate is available, the FDI or BDI methods should be employed, as both these methods have reduced variability relative to the FT+C method.

Conclusion

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

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Table

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

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FT+C	0.2	2.3	-4.3 – 4.6	0.931	-0.01 -0.07 – 0.09	0.927 (0.84 – 0.97)

Figure Legend

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.

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

Figure 1

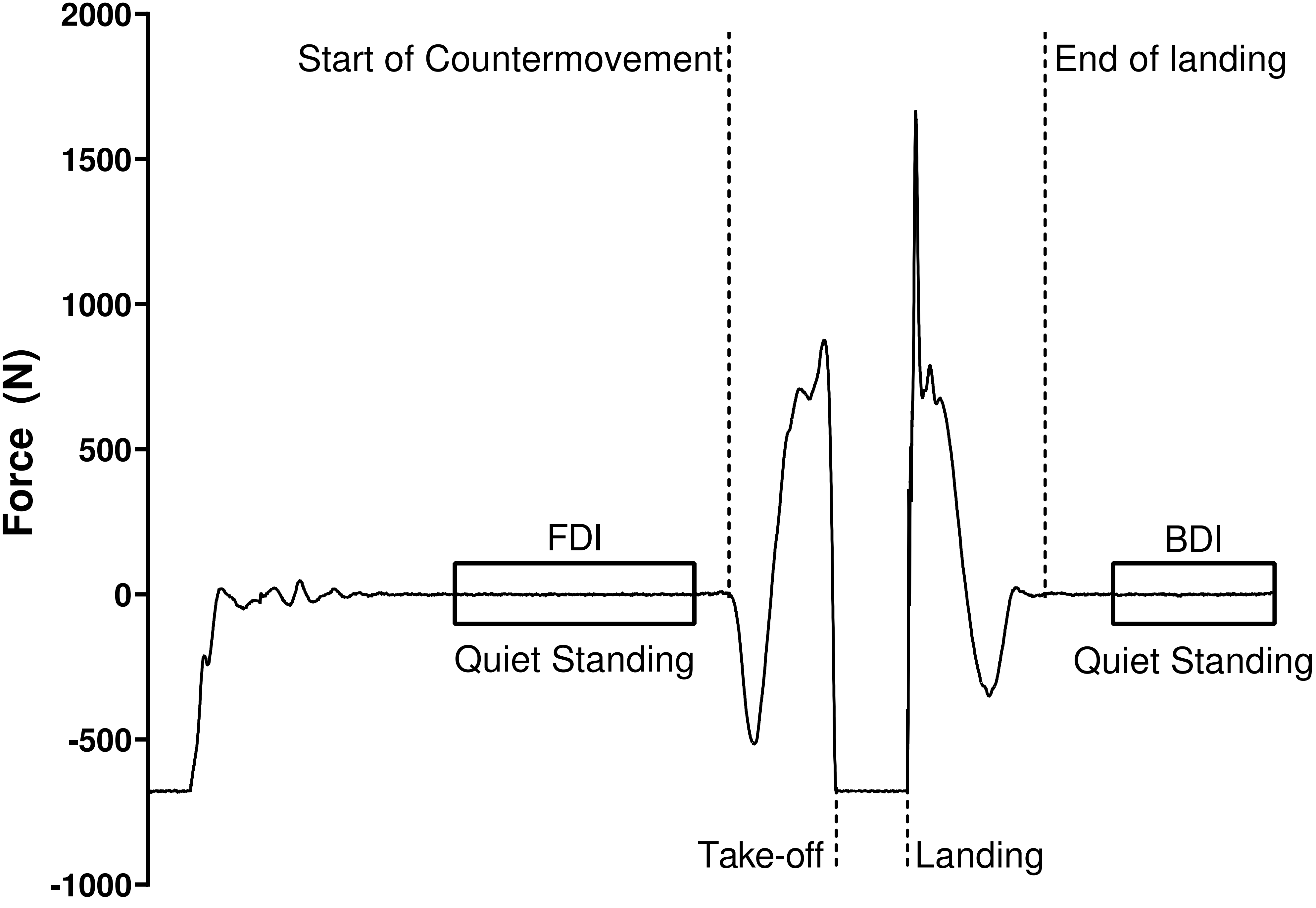
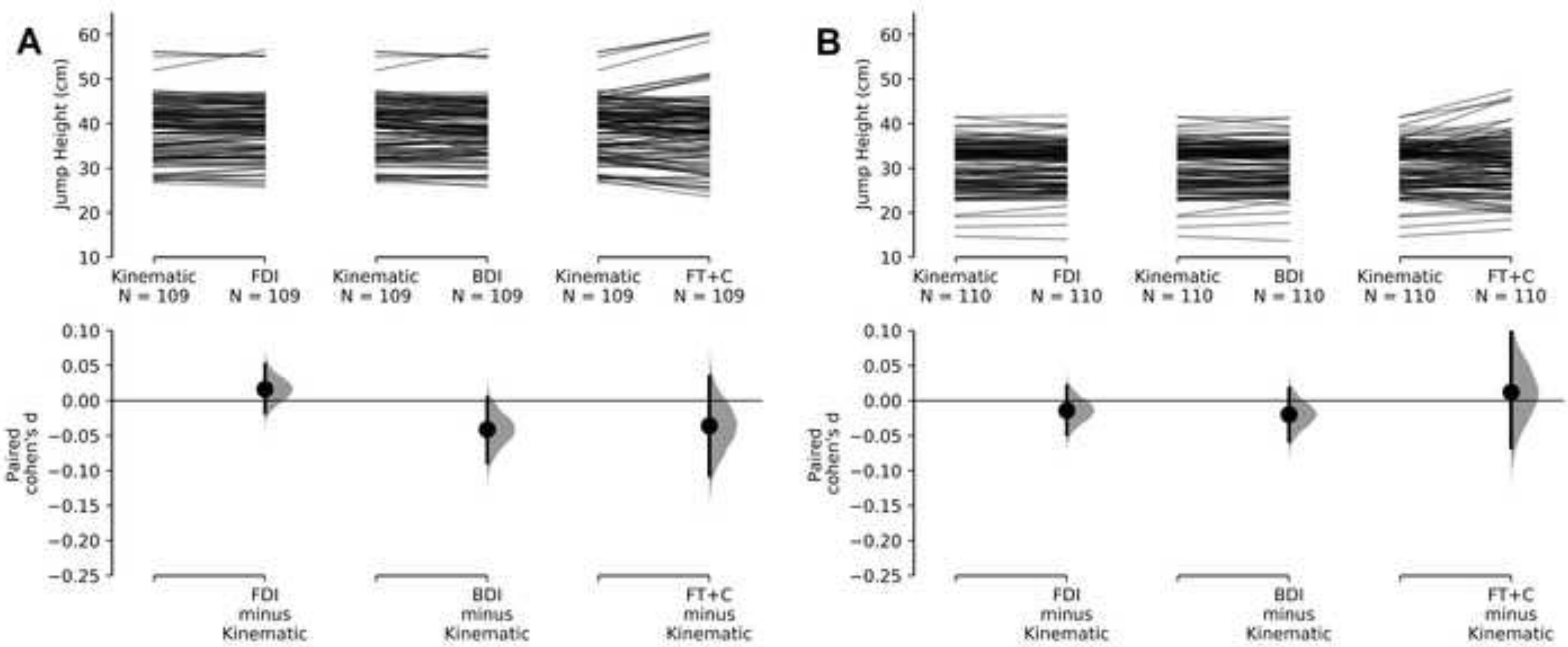

2000
1500
1000
500
0
-500
-1000
Force (N)
Start of Countermovement
End of landing
FDI
Quiet Standing
BDI
Quiet Standing
Take-off
Landing

Figure 2


A
B
Jump Height (cm)
60
50
40
30
20
10
Kinematic N = 109
FDI N = 109
Kinematic N = 109
BDI N = 109
Kinematic N = 109
FT+C N = 109
Kinematic N = 110
FDI N = 110
Kinematic N = 110
BDI N = 110
Kinematic N = 110
FT+C N = 110
Paired cohen's d
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
FDI minus Kinematic
BDI minus Kinematic
FT+C minus Kinematic