Comparisons of laboratory-based methods to calculate jump height and improvements to the field-based flight-time method

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Abstract

Laboratory methods that are required to calculate highly precise jump heights during experimental research have never been sufficiently compared and examined. Our first aim was to compare jumping outcome measures of the same jump, using four different methods (double integration from force plate data, rigid-body modelling from motion capture data, marker-based video tracking, and a hybrid method), separately for countermovement and squat jumps. Additionally, laboratory methods are often unsuitable for field use due to restrictions of equipment or time. Therefore, our second aim was to improve an additional field-based method (flight-time method), by combining this method with an anthropometrically-scaled constant. Motion capture and ground reaction forces were used to calculate jump height of twenty-four participants who performed five maximal countermovement jumps and five maximal squat jumps. Aim 1: Within-participant mean and standard deviation of jump height, flight distance, heel-lift and take-off velocity were compared for each of the four methods. During countermovement jumping, all four methods calculated jump height with low variability. During squat jumping, the double integration method had significant errors due to integration drift while all other methods had low variability. Rigid-body modelling was unable to determine the position of the centre of mass at take-off in both jumping movements and should not be used to calculate heel-lift or flight distance. Aim 2: The flight-time method was greatly improved with the addition of an anthropometrically-scaled heel-lift constant, enabling this method to estimate jump height and subsequently estimate power output in the field.

Introduction

Jumping is commonly used to gain insight into the fundamental principles that underlie human movement. This is because it requires coordination of multiple joints, and task requirements can be easily manipulated for careful experimental design [1, 2]. Additionally, it is commonly used for field-based estimates of athlete power [3, 4]. The widely used flight-time method calculates the distance travelled in the air [5-8], enabling estimates to be easily obtained in the field. However, this only accounts for one component of jump height, measuring the flight distance, while neglecting the heel-lift distance caused by ankle rotation prior to take-off. Therefore, the flight-time method underestimates jump height by approximately 10-12 cm [6, 9] compared to methods that more directly determine jump height [5, 6, 10]. Calculations of jump height require the application of more complex methods such as double integration of acceleration from force plate data [2, 5, 6], rigid-body modelling from motion capture data [10-12], marker-based video tracking [13, 14] or a hybrid method that combines motion capture and force plate data [10]. Double integration enables calculation of jump height using a single force plate, measuring changes in velocity and displacement of the COM between quiet standing and take-off. However, twice integrating the data can result in small measurement errors being compounded into large errors as data sampling time increases [15]. Rigid-body modelling and marker-based video tracking eliminate issues of integration drift, however these systems require tightly controlled laboratory conditions and can suffer from marker occlusion. Additionally, marker-based tracking assumes that COM displacement is equivalent to the tracked markers (pelvis markers in this study) and therefore does not consider changes in body posture while in the air. Rigid-body modelling tracks individual segments within the body, however this method requires complex data processing, commonly uses generic geometry scaling, ignores soft tissue deformation [16] and often combines the head, arms and trunk to form a single segment [1, 9, 17]. The hybrid method calculates heel-lift from marker-based video tracking and therefore only requires force plate data to be integrated once to calculate flight distance, reducing errors due to integration drift while eliminating the need for complex data processing. As this method combines two separate measurements it is critical that data are synchronised accurately.

Previous research has only compared methods that calculate jump height to methods that calculate flight distance [5, 6, 10], or compared methods that compute flight distance only [18]. Therefore, no study has compared methods that actually calculate jump height to one another. A comprehensive comparison is warranted to understand the relative merits of all approaches. At present there is no gold standard for calculating jump height as all methods have limitations, thus no method can be treated as a criterion. Both countermovement jumping (CMJ) and squat jumping (SJ) are frequently used in research [12, 13, 19].

However, SJ has a much longer time between quiet upright standing and take-off, as participants must descend and hold a static position at the bottom of the squat. Therefore, while SJ push-off time is shorter than CMJ execution time, the period over which double integration must occur is much greater, potentially resulting in large errors in displacements obtained via the double integration method [15]. Our first aim was therefore to provide detailed comparisons of four laboratory-based methods for determining jump height during CMJ and SJ.

As it is not always possible to implement laboratory-based methods, the flight-time method will still be used by various researchers and coaches in the field, despite this method only measuring flight distance [5-8]. Therefore, we additionally tested whether the flight-time method may be improved by accounting for heel-lift at take-off. Previous research has demonstrated that jumping movement patterns for the same person remain consistent between jumps [9, 20], thus the COM position at take-off is likely consistent for an individual. Adding an anthropometrically-scaled constant of heel-lift to the flight time method could provide better estimates of jump height, allowing this method to be used with estimated power output formulas, which drastically underestimate power if only the flight-time method is used [3, 4]. Therefore, the second aim of this study was to design and test a formula for an anthropometrically-scaled heel-lift constant to be used with the flight-time method.

Methods

Twenty-four participants (15 male and 9 female, mass = 71 ± 9 kg, height = 174 ± 8 cm) gave written informed consent to participate in this study. Ethics was approved by an institutional ethics review committee at The University of Queensland. Prior to testing, participants were given a pair of shoes (Gel Pursuit 2, Asics, Kobe, Japan) and a vest that they were instructed to tightly grasp during jumping to ensure arms were not used. Participants then performed a warm up at their own discretion to ready themselves for maximal jumping. Squat depth for CMJ was uncontrolled while SJ squat depth was set using a knee angle of 90 °, implemented by suspending a rope horizontally behind the participant that their thighs touched at the correct depth. Participants performed five maximal CMJ and five maximal SJ with at least 30 s rest, in a block-randomised order. Participants quietly stood upright for 2 seconds before all jumps, after which they either performed the CMJ in a fluid motion or in the SJ condition, they descended and held a squatted position for at least two seconds before pushing off.

The double integration method (DI) used GRF data (1000 Hz) recorded from two in-ground force plates (OR6-7, AMTI, MA, USA), one foot on each plate, using Qualisys Track Manager software (Qualisys Track Manager, Qualisys, Sweden). Data were exported to MATLAB (Mathworks, MA, USA) where a custom script calculated centre of mass (COM) vertical velocity and displacement of the body as the first and second integrals of acceleration (net force divided by body mass). Double integration was performed over the entire movement phase, from quiet upright standing through the countermovement (held for 2 seconds for SJ only) until take-off. Take-off velocity was used to calculate flight distance (distance travelled in the air) which was then summed with heel-lift (displacement of COM between quiet upright standing and the instant of take-off) to calculate jump height. Further details of jump height calculations are provided in Appendix A.

Motion capture (200 Hz) data were collected synchronously with GRF data (Qualisys Track Manager, Qualisys, Sweden) using an eight-camera, three-dimensional optoelectronic camera system (Oqus, Qualisys, AB, Sweden) and reflective markers placed on the body (Appendix A). For the marker-based video tracking method (MARKER), positions of 4 markers on the pelvis were averaged to approximate the pelvis COM (Appendix A). For the rigid-body modelling method (MODEL), positions of 34 markers were combined with a rigid-body model [21] using OpenSim software [22], estimating whole-body COM position as the COM of the rigid-body model (Appendix A). For MARKER and MODEL, jump height was calculated as the vertical position of the pelvis COM (MARKER) or body COM (MODEL) during standing, subtracted from the respective COM position at the apex of the jump. Heel-lift for MARKER and MODEL were calculated by interpolating the COM position to find the instant of take-off, using timing obtained from GRF data. Take-off velocity for MARKER and MODEL were calculated by differentiating respective COM positions from standing until take-off.

The hybrid method (HYBRID) was modified from Aragón-Vargas [10], with flight distance obtained from the DI method and heel-lift obtained from the MARKER method which were then summed to calculate jump height. During SJ, integration of GRF data were only required for the push-off phase to calculate flight distance (Appendix A). The HYBRID method reduces errors associated with integration drift because GRF data were only integrated once.

The flight-time method (FT) calculated flight distance from the time in the air, defined as the instant of take-off until landing. Take-off timing was obtained from the DI method, while landing was identified from the first point after take-off where vertical GRF reached 50 N, then tracked in reverse to find the first instance where vertical GRF was greater than zero. Time in the air was halved and input into a projectile motion equation to compute flight distance (Appendix A). Body position (hip, knee and ankle joint angles) during take-off and landing was also examined, as the FT method assumes respective joint angle were identical at both time points. Joint angles of the hip, knee and ankle, calculated using the rigid-body model, were interpolated to find joint angles at the instant of take-off and landing based on event timing from GRF data.

The anatomically scaled heel-lift constant was estimated to be equivalent to the vertical distance between the ankle and the ground at the instant of take-off (Figure 1), minus the vertical distance between the ankle and the ground during standing (**Ankle Height**, Figure 1). Foot angle relative to the ground at the instant of take-off across all participants was 61.4 ± 4.8 °. Therefore, to account for the foot not being perpendicular to the ground at take-off, the vertical distance from the ankle to the toe at take-off was calculated as the distance from the medial malleolus to the toes during standing, multiplied by sin(61.4). For simplicity, this has been written in the heel-lift constant formula below as 0.88

multiplied by **Foot Length** (Figure 1A and B). If shoes are worn, as is the case in this paper (Figure 1B), the sole of the shoe may slightly lift both the heel and the toes to different heights, resulting in a lift of the COM that must be accounted for. Therefore, the thickness of the shoe sole inferior to the toes must be included within the equation (**Sole Thickness**, Figure 1B). The heel-lift constant was implemented by calculating the following formula: $Constant = (0.88 * Foot\ Length) + Sole\ Thickness - Ankle\ Height$.

All statistics compare the within-participant mean variable magnitudes, and within-participant standard deviation (SD) of the same five jumps performed by each participant, calculated by four different methods. Therefore, if all methods accurately calculate each outcome variable, mean and within-participant SD for all methods would be identical. The null hypothesis for statistical tests was that each outcome variable mean value and within-subject variability would be the same across all calculation methods. From this point forward, all references to mean values and SD refer to the within-participant mean and within-participant SD, respectively. Outcome values for jump height, flight distance, heel-lift and take-off velocity were averaged, and SD's were calculated. D'Agostino & Pearson normality tests were performed on mean absolute values of jump height, flight distance, heel-lift distance, and take-off velocity and then mean values and SD were individually analysed using one way repeat measures ANOVA. If a significant main effect of method was found ($P < 0.05$), post hoc analysis was performed using a Bonferroni correction with Bonferroni corrected P values reported. As all jump height methods were applied to the same set of CMJ or SJ, increases in within-participant SD between methods were due to variability introduced by the method. Effect sizes of SD were calculated using the eta-squared method where required. Within-participant coefficients of variation (CV) was calculated for each method. If results did not pass normality, then a Friedman's test with a Dunn's multiple comparison test was performed. Heel-lift constant was evaluated using a Bland-Altman analysis comparing the HYBRID method to FT and FT + constant. A Bland-Altman analysis was used to compare the FT method to the flight distance calculated by DI. Differences in joint kinematics of the hip, knee and ankle during landing and at take-off were examined using paired t-tests.

Results

Countermovement Jumping

Time taken to perform the CMJ from upright standing until take-off was 1.26 ± 0.23 s. A main effect of method was reported for mean jump height, flight distance, heel-lift and take-off velocity, post hoc analysis results are reported in Table 1. A main effect of method was reported for within-participant SD of jump height, heel-lift and take-off velocity but not for flight distance. Within-participant mean jump height calculated with the DI method was the highest while MODEL was the lowest (Table 1). Post hoc analysis of CMJ height SD demonstrated that differences in variability between all methods was 0.04 cm or less which resulted in a low effect size of 0.03. The MODEL method calculated heel-lift much lower on average compared to DI and HYBRID/MARKER (2-3 cm). SD of heel-lift was significantly higher when calculated by DI compared to all other methods (0.03 cm), resulting in a moderate effect size of 0.22. Take-off velocity was not significantly different between DI/HYBRID and MODEL despite displaying significantly different values in flight distance (Table 1).

Squat Jumping

Time taken to perform the SJ from upright standing until take-off was 4.56 ± 0.46 s, which was 3.6 times greater than CMJ. For SJ, a main effect of method was reported for mean and SD of jump height, flight distance, heel-lift and take-off velocity, post hoc analysis are reported in Table 2. The DI method calculated an average jump height significantly lower than all other methods (Table 2) and within-participant SD in the DI method was significantly higher with a CV of 27% compared to the three other methods which had a CV of 3.4% or less. Heel-lift calculated by the DI method was -1.1 cm due to a large period over which DI must be performed, resulting in the position of the COM drifting significantly, to the point where the COM was recorded as a negative at the instant of take-off. This erroneously suggests that take-off was occurring before the COM reached standing height, paired with a SD of 6.4 cm, resulting in an unrealistically high CV of 573% (Table 2). Take-off velocity was not significantly different between DI/HYBRID and MODEL, despite MODEL calculating significantly higher values for flight distance.

Heel-lift constant

In both CMJ and SJ, within-participant heel-lift SD was less than 0.8 cm for all methods except DI during SJ. During CMJ, the FT method calculated flight distance as 32.3 ± 1.3 cm on average. Bland-Altman analysis indicated that the FT method alone underestimated CMJ height by 9.6 ± 1.5 cm compared to the HYBRID method, while FT + heel-lift constant overestimated jump height by 0.4 ± 1.6 cm compared to the HYBRID method. During take-off, hip joint angle was 18.1 ± 5.8 degrees, knee angle was 7.8 ± 2.5 degrees and ankle plantarflexion angle was 37.9 ± 5.3 degrees. During landing, hip angle was 23.5 ± 11.3 °, knee angle was 23.0 ± 10.6 ° and ankle plantarflexion angle was 26.8 ± 10.3 °. Therefore, all joints were significantly more flexed/dorsiflexed ($p < 0.019$) at the instant of landing compared to take-off. Subsequently, Bland-Altman analysis indicated that FT overestimated flight distance by 1.0 ± 1.3 cm compared to the flight distance calculated by DI.

Discussion

This study compared four laboratory-based methods for calculating jump height. The calculated CMJ height significantly differed between methods, however the SD range between methods was only 0.04 cm with a low effect size (0.03). Therefore, all four methods are appropriate to calculate repeated CMJ height. SJ height calculated by HYBRID and MODEL were not significantly different, while MARKER calculated SJ height significantly higher and DI calculated SJ height significantly lower than all other methods. SJ height SD was only significantly different when calculated by DI compared to all other methods, and therefore HYBRID, MARKER and MODEL provide equivocal jump height variance and are appropriate to calculate repeated SJ. The DI method however had clear errors for jump height and heel-lift, mean and SD (Table 2), as negative heel-lift has never been shown in any previous studies and no other methods showed similar changes. We believe this occurred due to small errors in body weight identification during quiet upright standing, due to small changes in GRF as the participant swayed during normal standing, which were then exponentially increased by twice integrating the data. It is likely that integration drift was also present during CMJ although to a much smaller degree, as DI had significantly higher heel-lift SD (0.03 cm) than all other methods and produced a moderate effect size (0.22). While DI may still be sufficient to calculate outcome measures during CMJ, the increase in time taken to perform the SJ movement produces large errors during the second integration of the data, rendering this method inappropriate for use with this movement.

Heel-lift mean values calculated by DI and HYBRID/MARKER methods during CMJ were within expected ranges (10-12 cm) based on previous studies [2, 6, 12], while heel-lift calculated by MODEL (8.8 cm) was significantly lower than all other methods. To investigate this, we examined the relationship between take-off velocity and flight distance which should be directly proportional as the only force acting on the body in the air is gravity. Mean take-off velocity was not significantly different between DI/HYBRID and MODEL methods but was significantly higher when calculated by MARKER. Therefore, this pattern between methods was expected to be replicated in the flight distance results. While DI/HYBRID and MARKER appeared as expected, flight distance calculated by MODEL was significantly higher than both other methods (Table 1). A similar finding was shown by Kibele [18], whose rigid-body model calculated a flight distance significantly higher than flight distance calculated by either DI or FT methods. Similar to Kibele [18] we also found that the FT method overestimates flight distance due to a more crouched posture (increased hip and knee flexion and increased ankle dorsiflexion) during landing compared to take-off. Therefore, as the FT method overestimates flight distance, we suspect the MODEL method must also be overestimating flight distance and underestimating heel-lift, due to inaccurate estimates of the COM position at take-off. Errors in the MODEL method could come from generic geometry scaling, rigid-body assumptions, and a combined head, arms and trunk segment [9, 16, 17]. Further analysis to examine this error in rigid-body modelling is required to improve the MODEL method. The MARKER method calculated a flight distance of only 0.01 cm less than FT on average and therefore it is possible that MARKER is also slightly overestimating flight distance. As variability of the MARKER method is still very low and proportions of flight distance and heel-lift to jump height are within expected ranges, this method appears to be suitable for comparing repeated measures of jump heights.

Heel-lift constant

To examine the effect of applying the heel-lift constant, we compared FT + constant to HYBRID and FT alone. Mean jump height values using FT were 9.6 ± 1.5 cm lower on average than HYBRID, while mean FT + heel-lift constant values were 0.4 ± 1.6 cm higher on average than HYBRID. Therefore, using the heel-lift constant reduced the calculated difference between FT and HYBRID methods by 9.2 cm on average. Thus, inclusion of the constant substantially improves field-based estimates of jump height, allowing this method to be used with power output estimation formulas [3, 4]. While the constant may appear to overestimate jump height by 0.4 cm, this is influenced by the FT method overestimating flight distance due to changes in body posture while in the air, as indicated previously [6, 10, 18]. While this constant will not change the results of assessing changes in jump height of the same athlete, the anthropometric scaling of this constant will identify differences in jump heights between athletes that would not be identified by the FT method alone. The heel-lift constant is therefore a valuable tool for coaches and researchers alike, and we recommend that this constant be included in all future applications of the FT method.

Perspective

No previous studies have compared methods that calculate jump height. Our results suggest that DI, HYBRID, MARKER and MODEL methods all calculate jump height with low variability and therefore any of the four methods may be used to calculate jump heights in repeated CMJ. The DI method is not recommended for SJ, due to integration drift that caused large errors because of increased time to perform the movement. All other methods were appropriate for SJ. The MODEL method is likely unable to correctly detect position of the COM at take-off which results in errors in heel-lift and flight distance. Therefore, research requiring calculation of heel-lift or flight distance should use DI, HYBRID or MARKER methods in CMJ and HYBRID or MARKER in SJ. Heel-lift distance appears to be very consistent during repeated maximal jumps. Therefore, heel-lift may be described by a constant based on anthropometric values that improves jump height measures of the FT method, enabling this method to better estimate jump height and subsequently power output in the field.

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Author contributions

All authors have made substantial contributions to the conception and design of the study, analysis and interpretation of data, revising it critically for important intellectual content and have approved the final version for submission.

Conflicts of Interest

There are no conflicts of interest.

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Tables

<table>
<tr><th colspan="5">Jump Height</th></tr>
<tr><td></td><td>DI</td><td>HYBRID</td><td>MARKER</td><td>MODEL</td></tr>
<tr><td>MEAN (CM)</td><td>43.2^{A}</td><td>42.0^{B}</td><td>42.9^{A}</td><td>41.4^{C}</td></tr>
<tr><td>SD (CM)</td><td>1.5^{A}</td><td>1.1^{B}</td><td>1.2^{BD}</td><td>1.3^{AD}</td></tr>
<tr><td>CV (%)</td><td>3.5</td><td>2.8</td><td>2.8</td><td>3.2</td></tr>
<tr><th colspan="5">Flight Distance</th></tr>
<tr><td></td><td colspan="2">DI / HYBRID</td><td>MARKER</td><td>MODEL</td></tr>
<tr><td>MEAN (CM)</td><td colspan="2">31.3^{A}</td><td>32.2^{B}</td><td>32.7^{C}</td></tr>
<tr><td>SD (CM)</td><td colspan="2">1.1</td><td>1.2</td><td>1.2</td></tr>
<tr><td>CV (%)</td><td colspan="2">3.8</td><td>3.9</td><td>4.0</td></tr>
<tr><th colspan="5">Heel-Lift</th></tr>
<tr><td></td><td>DI</td><td colspan="2">HYBRID / MARKER</td><td>MODEL</td></tr>
<tr><td>MEAN (CM)</td><td>11.9^{A}</td><td colspan="2">10.7^{B}</td><td>8.8^{C}</td></tr>
<tr><td>SD (CM)</td><td>0.8^{A}</td><td colspan="2">0.5^{B}</td><td>0.5^{B}</td></tr>
<tr><td>CV (%)</td><td>7.2</td><td colspan="2">4.5</td><td>6.0</td></tr>
<tr><th colspan="5">Take-off velocity</th></tr>
<tr><td></td><td colspan="2">DI / HYBRID</td><td>MARKER</td><td>MODEL</td></tr>
<tr><td>MEAN (m/s)</td><td colspan="2">2.46^{A}</td><td>2.65^{B}</td><td>2.45^{A}</td></tr>
<tr><td>SD (m/s)</td><td colspan="2">0.04^{A}</td><td>0.06^{B}</td><td>0.05</td></tr>
<tr><td>CV (%)</td><td colspan="2">0.02</td><td>0.02</td><td>0.02</td></tr>
</table>

Table 1: Countermovement jumping within-participant mean, SD and CV for jump height, flight distance, heel-lift and take-off velocity for the 4 methods compared. As hybrid is a combination of two methods this is represented as combined cells. Annotations specify multiple comparisons where different letters indicate significant differences between values ($p < 0.05$).

Jump Height †				
	DI	**HYBRID**	**MARKER**	**MODEL**
MEAN (CM)	27.0^{A}	40.4^{A}	41.4^{B}	39.9^{A}
SD (CM)	7.4^{A}	1.3^{B}	1.1^{B}	1.1^{B}
CV (%)	27.4	3.4	2.8	2.9
Flight Distance				
	DI	**HYBRID**	**MARKER**	**MODEL**
MEAN (CM)	28.1^{A}	29.9^{B}	30.9^{C}	31.3^{C}
SD (CM)	1.4^{A}	1.2	1.1	1.0^{B}
CV (%)	5.09	4.21	3.52	3.38
Heel-Lift †				
	DI	**HYBRID / MARKER**		**MODEL**
MEAN (CM)	-1.1^{A}	10.5^{B}		8.6^{A}
SD (CM)	6.4^{A}	0.5^{B}		0.4^{B}
CV (%)	573	4.58		5.07
Take-off velocity				
	DI	**HYBRID**	**MARKER**	**MODEL**
MEAN (CM)	2.33^{A}	2.41^{B}	2.60^{C}	2.40^{AB}
SD (CM)	0.06	0.05	0.06^{A}	0.05^{B}
CV (%)	0.03	0.02	0.02	0.02

Table 2: Squat jumping within-participant mean, SD and CV for jump height, flight distance, heel-lift and take-off velocity for the 4 methods compared. As hybrid is a combination of two methods this is represented as combined cells. Annotations specify multiple comparisons where different letters indicate significant differences between values ($p < 0.05$). † Indicates that a Friedman's test with a Dunn's multiple comparison correction was used.

Figures

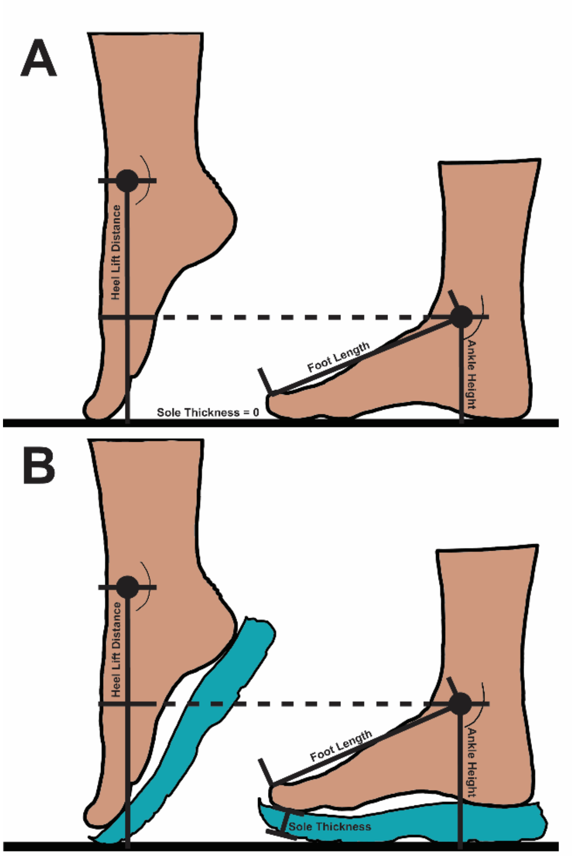

Figure 1: Position of the foot during standing (right) and at take-off (left). Difference in vertical distance between the two positions is assumed to match the heel-lift displacement of the COM. (A) indicates measures taken during jumping barefoot, (B) indicated measures taken while jumping shod.