Author/s:
Rantalainen, T;Hesketh, KD;Rodda, C;Duckham, RL

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DR TIMO RANTALAINEN (Orcid ID : 0000-0001-6977-4782)

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Validity of Hip-worn Inertial Measurement Unit Compared to Jump Mat for Jump Height Measurement in Adolescents

Rantalainen T.[1,2], Hesketh K. D.[1,] Rodda C.[2], Duckham R. L.[1,3]

[1] Deakin University, Geelong, Australia, Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences

[2] Gerontology Research Center, Faculty of Sport and Health Sciences, University of Jyväskylä, Finland

[3]Australian Institute for Musculoskeletal Sciences (AIMSS), Western Hospital, and Melbourne University, St. Albans, Australia,

Running head: Adolescent jump height with IMUs

Address for Correspondence and Reprints:
Dr Timo Rantalainen
Deakin University, Melbourne Burwood Campus, 221 Burwood Highway, Burwood, VIC 3125, Australia
Email: t.rantalainen@deakin.edu.au; Tel. +61 3 9251 7256; Fax +61 3 9244 6017

Abstract

Jump tests assess lower body power production capacity, and can be used to evaluate athletic ability and development during growth. Wearable inertial measurement units (IMU) seem to offer a feasible alternative to laboratory-based equipment for jump height assessments. Concurrent validity of these devices for jump height assessments has only been established in adults. Therefore, the purpose of this study was to evaluate the concurrent validity of IMU-based jump height estimate compared to contact mat-based jump height estimate in adolescents. Ninety-five adolescents (10-13 years-of-age; girls N=41, height = 154 (SD 9) cm, weight = 44 (11) kg; boys N=54, height=156 (10) cm, weight = 46 (13) kg) completed three counter-movement jumps for maximal jump height on a contact mat. Inertial recordings (accelerations, rotations) were concurrently recorded with a hip-worn IMU (sampling at 256 Hz). Jump height was evaluated based on flight time. The mean IMU-derived jump height was 27.1 (SD 3.8) cm, and the corresponding mean jump-mat-derived value was 21.5 (3.4) cm. While a significant 26% mean difference was observed between the methods (5.5 [95% limits of agreement 2.2 to 8.9] cm, p = 0.006), the correspondence between methods was excellent (ICC = 0.89). The difference between methods was weakly positively associated with jump height (r = 0.28, P = 0.007). Take-off velocity derived jump height was also explored but produced only fair congruence. In conclusion, IMU-derived jump height exhibited excellent congruence to contact mat-based jump height and therefore presents a feasible alternative for jump height assessments in adolescents.

Keywords: Wearable; Accelerometer; Concurrent; Methodology;

1. Introduction

Lower limb power production capacity has been established as a non-invasive indicator of athletic phenotype [1]. In addition to being an indicator of athletic ability [2,3], lower limb power production capacity has, for example, been linked with likelihood of falling among the elderly [4], and has been used to monitor response to therapeutic interventions, e.g. [5]. While many tests to evaluate lower limb power production capacity have been developed and validated [2,3], measuring jump height in a counter-movement jump test provides a reasonable assessment of lower limb power production capacity. Moreover, a jump test is a simple measure, which most population groups are able to perform [3,6].

Counter-movement jump performance is typically measured with force platforms [1] or motion capture systems [7] in the laboratory setting and with contact mats [8] or jump and reach devices [7] in the applied setting. More recently, low-cost portable inertial measurement units (IMU), which due to their wearable nature are not limited to a particular site in the field of play or laboratory, have been shown to be able to capture counter-movement jump performance in adults. The intra-class correlation coefficients (ICC) for flight-time derived jump height have been found to range from 0.8 to high 0.9 when validated against other systems capable of measuring flight-time in healthy young adults [9–13]. However, the differences in morphology [14] and power production capacity between adults and adolescents [15] raises the question of whether validity in adolescents can be inferred from adult populations. The validity of IMUs to assess jump performance in adolescents has yet to be established.

Therefore, the primary aim of this study was to evaluate the concurrent validity of IMU-derived jump height against jump-mat-derived jump height in a convenience sample of healthy adolescents. Based on validation studies in adult populations [9,12,16–18,18,19], it was hypothesised that good to excellent (based on ICC: good 0.60 to <0.75, excellent ≥ 0.75 [20]) agreement between IMU- and jump-mat-derived jump height would be observed.

2. Materials and Methods

Ninety-nine healthy adolescents (girls N = 45, boys N = 54) participated in this study. The children, aged 10-13 years, were drawn from an existing cohort participating in the ongoing Healthy, Active Preschool & Primary Years (HAPPY) study. In brief, the HAPPY study used a two-staged stratified random sampling procedure to recruit children from 64 pre-schools and 77-day care centres across Melbourne in 2008-2009 [21]. The data presented in this paper was extracted from the HAPPY Bone study, a sub-study of the larger HAPPY study. The primary purpose of the HAPPY bone study was to explore the association between sedentary behaviour and bone health. In 2016, from the pool of 450 participants remaining in the HAPPY study, all N = 208 participants in the top and the lowest tertile of sedentary behaviour with valid accelerometry in at least two previous HAPPY study data collection time points were invited to take part in the sub-study. The study was conducted in accordance with the Declaration of Helsinki. The study protocol was approved by the Deakin University Human Research Ethics Committee (HEAG-H 88_2016). All participants gave verbal assent and their guardians gave written informed consent prior to participating.

The participants were asked to attend a single testing session at the Deakin University Burwood campus clinical laboratory. Age, height (Holtain limited, Crymmych, Pems., U.K.

stadiometer to nearest 0.1 cm) and weight (UC-321 A&D Co., Ltd., Tokyo, Japan electronic scales to nearest 0.1 kg) were recorded at the beginning of the testing session. A standardised warm-up (comprising 5 minutes of jogging, 5 mins of a series of dynamic jumps, finishing with fast feet and stretching), and familiarisation to the study procedures was performed prior to testing to ensure optimal performance. Following the familiarisation, participants were fitted with a wearable IMU recording 3D accelerations and gyrations (x-BIMU Bluetooth Kit, x-io Technologies Limited, UK, gyroscope [measurement range ±2000 °/s], accelerometer [measurement range ±16 multiples of gravitational acceleration], 16-bit A/D conversion, sampled at 256 Hz). The IMU was worn on an elastic belt, and positioned on the right hip just below the iliac crest in line with the mid-axial line. Subsequently, participants were asked to complete three maximal counter-movement jumps on a jump mat (Smartjump, Fusion Sport, Sumner Park, QLQ, Australia). Participants were asked to stand still on the centre of the jump mat with their feet shoulder width apart and hands positioned on their hips. They were then instructed to complete a counter-movement jump with their preferred counter-movement depth for maximal jump height while keeping their hands on their hips. They were told to land softly by allowing their knees to bend, and to remain standing still after the jump. The participants were given 30 seconds rest between jumps and were required to complete a total of three jumps. For this study, the jump height of the three maximal jumps given by the jump mat software were recorded in centimetres (cm) and the mean of the three jumps was used within the analyses.

2.1. Numerical analysis

Numerical analysis for IMU-recorded data was conducted with custom-written Matlab scripts (version 8.6.0.267246, R2015B, MathWorks Inc., USA). Vertical acceleration was obtained from the IMU recording by estimating the sensor orientation with respect to the direction of gravitational acceleration using the gradient descent algorithm developed by Madgwick et al. [22] (https://github.com/tjrantal/madgwickAHRS). The gyrations and accelerations were low-pass filtered with a 40 Hz 4th order zero-lag low pass Butterworth filter prior to applying the gradient descent algorithm. Only vertical acceleration was used for further analyses.

Epoch (samples included) of interest surrounding the jump was defined manually. Integration drift was minimised, and gravitational acceleration removed by the following procedure. First, trapezoidal integration was applied on the acceleration to derive velocity. Second, first order polynomial

$$velocity = a + b * time$$

was fitted to the derived velocity using the least squares method. Third, the slope (b) of the fit was subtracted from the vertical acceleration, and this slope-corrected vertical acceleration was used for all further analysis. Subsequent to the drift-correction procedure, vertical velocity was calculated from the vertical acceleration with trapezoidal integration. Epoch of interest was re-defined (integration drift removal procedure was repeated after each definition of an epoch) as zero velocity was needed before and after the jump, as ensured by the protocol. As reported by others (e.g. [9]), jump height was calculated based on maximal vertical velocity (maximal velocity-derived jump height [cm])

$$jump\ height_{velocity-derived} = \frac{maximal\ vertical\ velocity^2}{2g}$$

, where $g = 9.81\ m/s^2$. Jump height was also calculated based on flight time determined as the time elapsed between the maximal and minimal vertical velocity (flight-time-derived jump height [cm])

$$jump\ height_{flight-time-derived} = \frac{g * flight\ time^2}{8}$$

,where $g = 9.81\ m/s^2$. Mean concentric power with respect to body mass (Power [W/kg]) was calculated as the mean of acceleration multiplied by velocity from the epoch between maximal velocity and the last velocity data point that was ≤ 0 prior to maximal velocity[23]. The mean of the three trials was used for statistical analyses.

2.2. Statistical analysis

For statistical power purposes, an N = 27 could be considered appropriate for an exploration of correspondence between two methods. We used all available data, therefore with a sample size of N=99 this study is adequately powered to evaluate the external validity of these two measures[24]. Descriptive statistics (age, height, weight) were compared between sexes with independent samples t-tests. Data from boys and girls were pooled for all subsequent analyses.

The concurrent validity of the IMU-derived flight-time-derived jump height and maximal velocity-derived jump height was compared against the flight-time-derived jump height given by the jump mat. Mean difference, 95% limits of agreement (95% LoA), Pearson correlation coefficient (r), and intra-class correlation coefficient (calculated for consistency [25], ICC) are reported to indicate validity. ICCs were used to describe the correspondence as poor (< 0.40), fair (0.40 to < 0.60), good (0.60 to <0.75) or excellent (≥ 0.75)[30]. Statistical significance for the mean difference between repeated measures, and between methods was evaluated with paired t-tests. Bland Altman plots [26] are also presented to visually display the mean difference and range of difference (mean bias and 95% LoA) between measures. Dependence from the absolute value was evaluated with Pearson correlation coefficient (r) between the mean of the methods, and the standard deviation between the methods. Mean (SD) are reported where applicable. A Pearson correlation coefficient was also used to evaluate the association between measured jump heights, and power. Statistical analyses were run on Matlab (version 8.6.0.267246, R2015B, MathWorks Inc., USA) and statistical significance was set at $p \leq 0.05$.

3. Results

Out of the 208 invited to take part 118 indicated interest in taking part, and after excluding individuals with past bone fractures a total of N = 99 took part in the present experiment. Complete datasets were not obtained for four girls due to non-compliance with study protocols and therefore data is reported for N = 95 (girls N = 41, boys N = 54) of the N = 99 participants. The mean age, height, and weight were 12.2 (SD 0.9) y, 154 (9) cm, and 44 (11) kg for girls, respectively. The respective values for boys were 12.2 (0.8) y, 156 (10) cm, and 46 (13) kg. As mentioned above, sexes were pooled for analyses, and only the pooled results are presented below.

The mean IMU-derived performance values were: (1) velocity-derived jump height 29.3 (5.6) cm, (2) flight-time-derived jump height 27.1 (3.8) cm, and (3) power 22.4 (4.4) W/kg. The mean jump-mat-derived jump height was 21.5 (3.4) cm.

Significant mean differences were observed between IMU- and jump-mat-derived estimates of jump height for both maximal velocity-derived jump height (mean difference 7.8 [95% LoA -0.6 to 16.2] cm, $p < 0.001$) and flight-time-derived jump height (mean difference 5.5 [95% LoA 2.2 to 8.9] cm, $p = 0.006$). The correspondence between IMU- and jump-mat-based methods was fair for maximal velocity-derived jump height (ICC = 0.57), and excellent for flight-time-derived jump height (ICC = 0.89) (Figure 1). The difference between IMU- and jump-mat-based methods was dependent on jump height for both maximal velocity-derived jump height ($r = 0.56$, $P < 0.001$) and flight-time-derived jump height ($r = 0.28$, $P = 0.007$) with larger difference between methods with higher jumps compared to lower jumps (Figure 2). The correspondence between IMU-derived maximal velocity-derived jump height and flight-time-derived jump height was good (ICC = 0.62) (Figure 1). Weak to moderate positive association was observed between jump mat and IMU-derived jump-heights and IMU-derived power (Figure 3).

***Insert Figure 1, Figure 2 and Figure 3 roughly here ***

4. Discussion

The primary finding of the study was that IMU-assessed flight-time-derived jump height exhibits excellent concurrent validity with jump-mat derived jump height, whereas maximal velocity-derived jump height exhibited only fair agreement to jump-mat derived jump height. However, a systematic difference was found between IMU- and jump-mat-derived jump heights, and this difference was dependent on the jump height with a larger difference between methods for higher jumps compared to lower jumps. The agreement between the IMU-derived jump heights determined based on flight-time and take-off velocity was good. These results are consistent with those reported for young healthy adults [9,16,17,19] in suggesting that IMUs provide a valid measure of jump height in healthy adolescents.

The present results on concurrent validity based on flight-time-derived jump height were in line with previous research using young adults as the participants [9,16,17,19]. The previous studies have found excellent concurrent validity against force plate and motion capture systems (ICCs ranging from 0.83 to 0.98 [9,16,17,19]. Also in line with previous studies in young adults, poorer concurrent validity compared to flight-time-derived results was observed with take-off velocity-derived jump height (ICC = 0.75; [9]). The treatment of the measured parameters (flight time, and maximal take-off velocity) cannot explain the difference in concurrent validity since they are both squared and used in the numerator. While we attempted to minimise integration drift in numerical analysis, the poorer concurrent validity of maximal take-off velocity-derived jump height compared to flight time-derived jump height is likely caused by the error included during integration (McMaster et al., 2014). Moreover, there is likely movement-velocity dependent effects on the IMU-derived jump height estimates as indicated by the significant association between the difference between methods and jump height. This is likely to be explained by the difficulties in coupling the IMU and the jumper. Previous IMU validation research in young adults has shown that the ability of an IMU harness to restrict unwanted movements gets worse with increasing movement velocity [27,28], and although we did not quantify this in the present study, it is likely to be true for a hip-worn IMU as well. The flight-time-derived results may have been less-affected by this issue compared to the take-off velocity-derived results as the magnitude of instantaneous velocity is not considered in the former but is in the latter.

The finding that velocity-derived jump height estimate exhibited poorer concurrent validity compared to flight-time-derived jump height warrants consideration. In particular, it raises the question of whether it is reasonable to estimate power from hip-worn IMUs. Power is dependent on velocity (power relative to body mass = acceleration x velocity). Since take-off velocity-derived jump height was found to exhibit only good correspondence to contact-mat-derived jump height, it brings into question whether IMU-assessed power estimates have limited validity as well. In contrast to our findings, Requena et al. [12] explored IMU-assessed take-off velocity-derived jump height estimates in adults and found excellent concurrent validity compared to a force plate and to motion capture. The participants in Requena et al. [12] were professional soccer players, and this difference between participant groups may partially explain the discrepancy between results in this study and those reported by Requena et al. [12]. Nevertheless, the concurrent validity of IMU-derived power estimates was not explored in the present study, and an explicit examination of the concurrent validity would be required to determine the validity of IMU-derived power estimates.

Taken together our findings indicate that IMU-assessed flight-time-derived jump height is a valid measure of jump performance in adolescents. However, the systematic difference observed between methods indicates that IMU-derived jump height results cannot be directly compared with jump mat-derived jump height results. Such comparisons require careful calibration between the methods. IMUs are wearable and wireless and hence enable performance testing in any location of the field of play, including during game play [29,30]. This freedom of testing location offers a significant advantage over other jump height testing methods by, for example, enabling recording of all jumps in a practice session or a game for load monitoring [31] or game analysis purposes.

This study had some limitations. Firstly, for practical reasons we used a jump mat to estimate concurrent validity as our ‘gold standard’ measure. In general, laboratory-based methods such as a force plate or three-dimensional motion capture could be considered more appropriate methods to use as the gold standard. Related to this, the IMU-derived power estimate was unable to be validated, and instead validity (or lack of) was inferred based on maximal velocity. It is possible that power estimate may be valid, even though maximal take-off velocity-derived jump height is not, because a longer epoch (in this study the concentric phase) can be considered in power estimates instead of a an instantaneous value. Nevertheless, jump mats have been shown to exhibit excellent external validity against force plates [8,32], and may be considered a reasonable reference for concurrent validation. Finally, maximal positive and negative velocity were used as the instants in defining flight time. This will lead to an overestimate of the flight time because due to dynamics maximal velocity occurs prior to actual take-off, and minimal velocity (i.e. highest velocity towards the ground) occurs after the actual touchdown. These instants were used because there is no other conspicuous characteristic of acceleration or velocity that can be used to define the actual take-off and touchdown instants. This is also why congruence rather than absolute agreement was explored in the present paper. As regards to the strengths of the study, we had a relatively large sample of both boys and girls with a relatively good spread of performance capacities, which enabled evaluation of concurrent validity with a high degree of statistical confidence.

In conclusion, while the absolute values differ significantly and cannot be used interchangeably, IMU flight-time-derived jump height exhibited excellent congruence to jump-mat derived jump height and thus provides a feasible measure of jump performance in adolescents. On the other hand, take-off velocity-derived jump height showed only fair concurrent validity. Therefore, flight-time-derived jump height should be preferred over velocity-derived jump height or velocity-dependent power as a measure of functional ability if IMUs are utilised in adolescents.

5. Perspectives

Taken together our findings indicate 1) that IMU-assessed flight-time-derived jump height is a valid measure of jump performance in adolescents, 2) that flight-time-derived jump height should be preferred over maximal velocity-derived jump height in assessing jump performance with hip-worn IMUs in adolescents, and 3) that IMU-derived jump height results should not be directly compared with jump mat-derived jump height results due to systematic difference between the methods. Although jump mats and jump-and-reach devices are highly portable they are limited to a single location while testing. IMUs can be used to monitor performance in any location of the field of play, therefore providing an appealing alternative to other portable methods to assess adolescent jump performance.

Conflict of interest statement

None of the authors have conflicts of interest to report.

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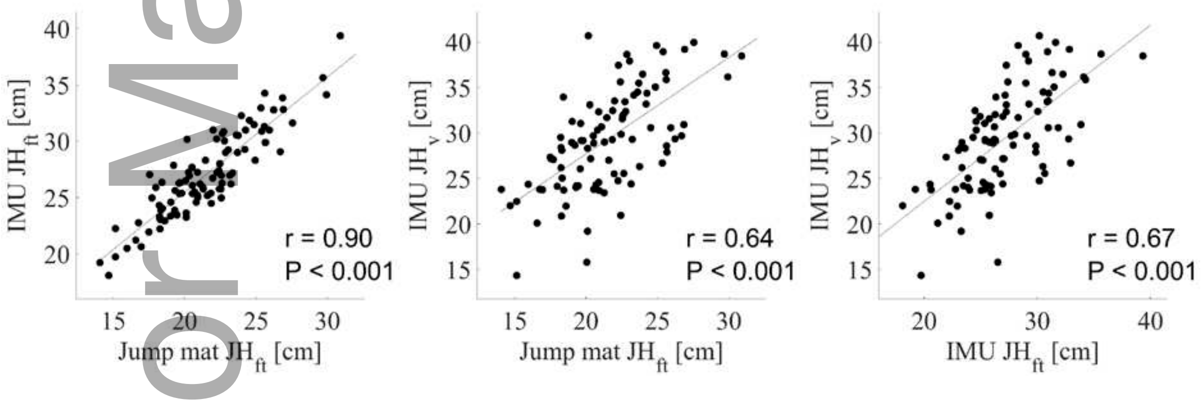
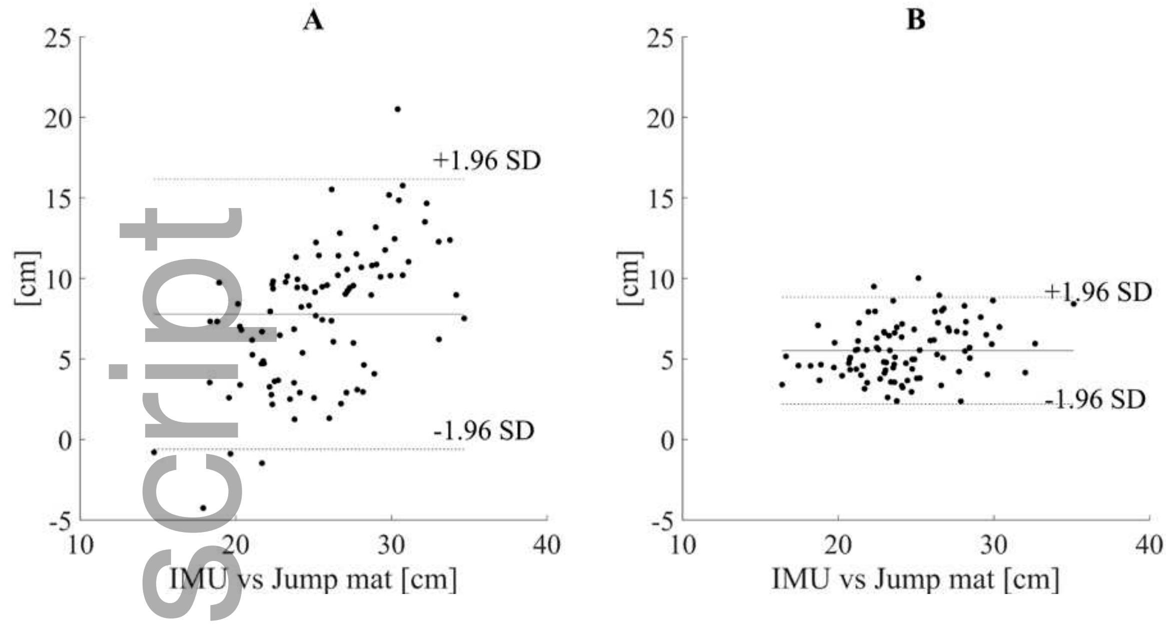
FIGURE LEGENDS

Figure 1. Scatterplots of jump-mat and IMU-derived jump height based on flight time plotted against inertial measurement unit-derived (IMU) jump height. JH_v = jump height based on take-off velocity. JH_{ft} = jump height based on flight-time.

Figure 2. Bland Altman plots of agreement between inertial measurement unit-derived (IMU) and jump-mat-derived jump heights. A: IMU take-off velocity-derived jump height, B: IMU flight-time-derived jump height.

Figure 3. Scatterplots of jump mat and inertial measurement unit-derived (IMU) jump height plotted against IMU-derived power. JH_v = jump height based on take-off velocity. JH_{ft} = jump height based on flight-time.




A
B
25
20
15
10
5
0
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[cm]
+1.96 SD
-1.96 SD
10
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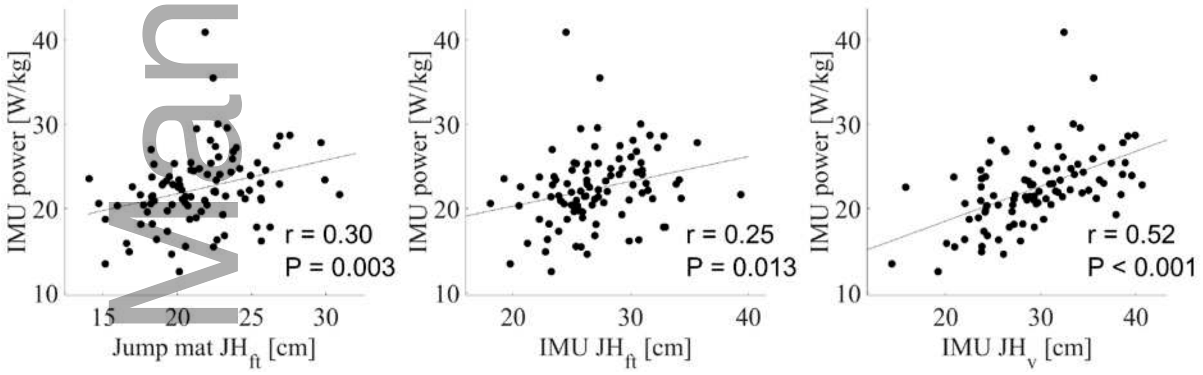
30
40
IMU vs Jump mat [cm]


IMU power [W/kg]
40
30
20
10
r = 0.30
P = 0.003
15
20
25
30
Jump mat JH$_{ft}$ [cm]
r = 0.25
P = 0.013
20
30
40
IMU JH$_{ft}$ [cm]
r = 0.52
P < 0.001
IMU JH$_{v}$ [cm]