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| **Corresponding Author:** | Iain Richard Spears, BEng., PhD.<br>Newcastle University<br>Newcastle upon Tyne, UK UNITED KINGDOM |
| **First Author:** | Shaun Mclaren, BSc, PhD |
| **Order of Authors:** | Shaun Mclaren, BSc, PhD |
| | William Evans, BSc, PhD |
| | Brook Galna, BSc, PhD |
| | Matthew Portas, BSc, PhD |
| | Matthew Weston, BSc, PhD |
| | Iain Richard Spears, PhD |
| **Abstract:** | <p class="aaNormal">Horizontal jumps are discrete, fast, over-ground movements requiring coordination of the centre of mass (CoM) and base of support and are routinely assessed in sports settings. There is currently no biomechanics-based system to aid in their quick and objective large-scale assessment. In this paper, we describe a practical system which uses a single low-cost depth-sensing camera and point-cloud processing (PCP) to capture whole-body centre of mass (CoM) and foot kinematics. Fourteen participants performed 10 single-leg horizontal jumps for distance. Foot displacement, CoM displacement, CoM peak velocity and CoM peak acceleration in the anterior-posterior direction of movement were compared with a reference <span style="color:black">15-segment criterion model,</span> captured concurrently using a nine-camera motion capture system (Vicon Motion Systems, UK). Between-system Pearson&rsquo;s correlations were very-large to near-perfect (n = 140; foot displacement = 0.99, CoM displacement = 0.98, CoM peak velocity = 0.97, CoM peak acceleration = 0.79), with mean biases being trivial&ndash;small (-0.07 cm [0.12%], 3.8 cm [3.5%], 0.03 m&middot;s<sup>-1</sup> [1.6%], 0.42 m&middot;s<sup>-2</sup> [7%], respectively) and typical errors being trivial&ndash;small for displacement (foot: 0.92 cm [0.8%]; CoM: 3.8 cm [3.4%]) and CoM peak velocity (0.07 m&middot;s<sup>-1</sup> [4.3%]), and large for CoM peak acceleration (0.72 m&middot;s<sup>-2</sup> [15%]). Limits of agreement were -1.9 to 2.0 cm for foot displacement, -11.3 to 3.6 cm for CoM displacement, -0.17 to 0.12 m&middot;s<sup>-1 </sup>for CoM peak velocity and -2.28 to 1.43 m&middot;s<sup>-2 </sup>for CoM peak acceleration. The single camera system using PCP was able to capture CoM and foot kinematics during horizontal jumps with acceptable precision. Further work to improve estimates of CoM accelerations and validation across a wider range of populations are warranted. <o:p></o:p></p> |

# Fast reconstruction of centre of mass and foot kinematics during a single-legged horizontal jump: A point-cloud processing approach

McLaren, S.J.[1,2], Evans, W[3]., Galna B[45], Portas, M.D[7], Weston, M[6], Spears, I.R.[4*]

[1]Newcastle Falcons Rugby Club, Newcastle upon Tyne, UK.

[2]Department of Sport and Exercise Sciences, Durham University, Durham, UK

[3]Faculty of Health Sciences and Wellbeing, Exercise, Sport and Rehabilitative Therapies, University of Sunderland, Sunderland, UK.

[4]School of Biomedical, Nutritional, and Sport Sciences, Newcastle University, Newcastle, UK

[5]College of Science, Health, Engineering and Education, Murdoch University, Western Australia, Australia

[6] Institute for Sport, Physical Education & Health Sciences, University of Edinburgh, UK

[7]Technical Directorate, The Football Association, St. George's Park, Burton upon Trent, UK

[*]Corresponding Author

Dr. Iain R. Spears, School of Biomedical, Nutritional and Sport Sciences, Faculty of Medical Sciences, Newcastle University, Newcastle Upon Tyne, UK

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## Abstract

Horizontal jumps are discrete, fast, over-ground movements requiring coordination of the centre of mass (CoM) and base of support and are routinely assessed in sports settings. There is currently no biomechanics-based system to aid in their quick and objective large-scale assessment. In this paper, we describe a practical system which uses a single low-cost depth-sensing camera and point-cloud processing (PCP) to capture whole-body centre of mass (CoM) and foot kinematics. Fourteen participants performed 10 single-leg horizontal jumps for distance. Foot displacement, CoM displacement, CoM peak velocity and CoM peak acceleration in the anterior-posterior direction of movement were compared with a reference 15-segment criterion model, captured concurrently using a nine-camera motion capture system (Vicon Motion Systems, UK). Between-system Pearson's correlations were very-large to near-perfect (n = 140; foot displacement = 0.99, CoM displacement = 0.98, CoM peak velocity = 0.97, CoM peak acceleration = 0.79), with mean biases being trivial–small (-0.07 cm [0.12%], 3.8 cm [3.5%], 0.03 $m \cdot s^{-1}$ [1.6%], 0.42 $m \cdot s^{-2}$ [7%], respectively) and typical errors being trivial–small for displacement (foot: 0.92 cm [0.8%]; CoM: 3.8 cm [3.4%]) and CoM peak velocity (0.07 $m \cdot s^{-1}$ [4.3%]), and large for CoM peak acceleration (0.72 $m \cdot s^{-2}$ [15%]). Limits of agreement were -1.9 to 2.0 cm for foot displacement, -11.3 to 3.6 cm for CoM displacement, -0.17 to 0.12 $m \cdot s^{-1}$ for CoM peak velocity and -2.28 to 1.43 $m \cdot s^{-2}$ for CoM peak acceleration. The single camera system using PCP was able to capture CoM and foot kinematics during horizontal jumps with acceptable precision. Further work to improve estimates of CoM accelerations and validation across a wider range of populations are warranted.

Short Title: A practical tool for the measurement of center of mass and base of support kinematics

## Keywords

movement screening, gait analysis, centre of mass, markerless

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## Introduction

Movement screening forms a regular component of athlete monitoring, providing important information on general movement skills and physical performance potentials (Read et al., 2017). Horizontal jumps are common to many screening batteries as a proxy measure of explosive ability (e.g., Strokosch et al., 2018). These tests involve a coordinated pattern of countermovement, body rotation and arm swing to generate maximal anterior-posterior displacement, velocity, and acceleration of the center of mass (CoM) on take-off and then control CoM above the new landed position of the feet (Wakai and Linthorne, 2005). In research settings, these kinematic outcomes are quantified directly using force plates or marker-based motion capture (Colyer et al., 2018). In field settings, jump performance is assessed using a tape measure (McCubbine et al., 2018) and technique assessed visually (Padua et al., 2015). Such methods are time-consuming and often with low inter-rater reliability (Lindblom et al., 2020). There are other commercial systems used in the field based on planar switches (e.g., Optojump (Microgate, Italy)) but these are currently only track the feet, potentially missing important features of jump performance.

There are several emerging technologies for the simultaneous measurement of foot and whole-body CoM kinematics which have potential for monitoring jump performance. Studies using multi-segment inertial measurement units have reported errors for feet and CoM positions of <1cm and < 2.57cm, respectively (Fasel et al., 2017). While likely to be acceptable for the present purposes, the costs and ease-of-use for large-scale screening programmes are prohibitive. A potential alternative is computer vision (Colyer et al., 2018). Skeletal tracking, in which artificial intelligence (AI) is used on images to infer on whole-body joint positions (Colyer et al., 2018), provides accurate estimates of kinematic parameters in some poses (Galna et al., 2014; Eltoukhy et al., 2017). The errors for foot position, however, can be quite high (>10cm (Xu and McGorry, 2015)). In contrast, point cloud processing (PCP), in which raw depth data is converted directly into 3D landmark coordinates, has been shown to achieve greater levels of accuracy. Notably, studies using PCP have consistently reported errors of <1cm for the foot (Paolini et al., 2013), ankle (Geerse et al., 2019), pelvis (MacPherson et al., 2016) and knee (Timmi et al., 2018). In addition, PCP has also been applied (albeit using multiple cameras) to measure CoM kinematics with similar levels of accuracy (Kaichi et al., 2019).

To date, PCP has so far been restricted to the analysis of cyclical, slow and relatively stationary activities. Whether this technology can track simultaneously the kinematics of the foot and CoM during discrete, fast over-ground movements involved in the horizontal jump remains to be determined. This study will describe the development and examine the criterion validity of PCP for the quantification of single-leg horizontal jump performance (Figure 1ai) in terms of displacement, velocity and acceleration outcomes. This single-legged jump is a more challenging version of the standing long jump, requiring the athlete to jump as far as possible horizontally from one foot to the other - requiring them to control their CoM in relation to a small base of support on landing. The specific aim of our study is to quantify the criterion validity of the displacement, velocity and acceleration outcomes based on PCP against those from a laboratory-grade system for the single-legged jump.

## Methods

The study received ethical approval from The University of Sunderland's Ethics committee. Fourteen physically active males (age: 28 ± 10 years, stature: 181 ± 9 cm, body mass: 82 ± 10 kg, BMI: 24.9 ± 2.7 kg·m$^{-2}$) volunteered and provided written informed consent. All participants were free from injury and, after a warm-up, performed single-legged horizontal jumps at one-minute intervals within the capture volume of the PCP and laboratory systems (Figure 1ai).

*Criterion three-dimensional system:* The criterion method of quantifying foot and CoM kinematics was a nine-camera optoelectronic system (Bonita B10, Vicon motion systems, Oxford, UK) at 100 Hz. Using a 19-segment plug-in gait model, markers were placed bilaterally on anatomical landmarks (Vicon motion systems, Oxford, UK). Trajectory data were low-pass filtered using a fourth-order Butterworth filter with cut-off frequency of 6 Hz.

*Depth sensor system:* The PCP-based system created is based on custom-written algorithms developed by Pro-Football Support Ltd using C# script in the Unity3D gaming engine. A low-cost depth sensing camera (Kinect™ V2, Microsoft, USA) was positioned at 0 mm, 1850 mm, and 3740 mm in the medial-lateral (x-axis), superior-inferior (z-axis) and anterior-posterior (y-axis) directions relative to the global origin of the criterion system (Figure 1ai and ii). The camera was tilted by -30$^{o}$ about the x-axis. This configuration was considered optimal in terms of maximising the capture volume, as determined by trial-and-error. Using a rigid calibration frame (600 × 2000 mm) positioned 740 mm anterior to the global origin, a 3x3 rotation matrix was determined, capable of transforming point cloud coordinates from the camera to criterion global system. Specifically, four strips (5 × 5 mm) of retroreflective tape were glued to the apices of the frame (Figure 1ai, Superior View) giving four coplanar points (P1, P2, P3 and P4) at known locations in the global system, and capable of being tracked in the camera system ($P1_{cam}$, $P2_{cam}$, $P3_{cam}$ and $P4_{cam}$). Unit vectors from $P1_{cam}$ to $P2_{cam}$ ($U_1$), $P1_{cam}$ to $P3_{cam}$ ($U_2$) and their cross-product ($U_3 = U_1 x U_2$) were used to create a 3 × 3 rotation matrix ($U_1$ = top row, $U_2$ = middle row, $U_3$ = bottom row). The calibration frame was then removed from the testing area, and subsequent point cloud data were transformed from the camera to global system ensuring that the practical and criterion data were aligned for all tests.

Following Paolini (2014), coloured markers were attached to the feet of each participant (Figure 1aii), enabling to reconstruct the foot position from the point cloud data. These foot markers included two retroreflective strips spaced 70mm apart, causing two regions of localised overexposure of the infrared image (Figure 1aiii). Following MacPherson et al. (2016), a virtual midpoint between these regions was created (Figure 1aiii, inset), enabling to identify a pixel at the centre of the foot marker. These pixel coordinates (2D) were then fed into the 3D point cloud data to acquire the relevant 3D position of the foot marker. The whole-body CoM reconstruction used markerless PCP based on the entire point cloud from the anterior surface of the athlete (Figure 1aii and iii). The processing involved 5 stages conducted on a frame-by-frame basis. First, points visible in the current frame and before the tests were identified and removed. Second, points with fewer than 5 neighbouring points within a radius of 5cm were identified and removed. Third, a mean 3D centroid position of all remaining points was calculated and used to position a cylindrical volume around the athlete (shown as a blue circle and rectangle in Superior and Sagittal view, respectively [Figure 1ai]). The dimensions (height = 2m, diameter 1.2m) were determined prior to testing and considered to be optimal in terms of maximising the number of points used, whilst minimising the risk of random clusters (due to camera artefacts, reflection etc) being included in the CoM calculation. Points outside of this volume were removed, thus leaving a 'clean' point cloud representation of the anterior surface of the athlete (Figure 1aii). The position of the CoM (i.e. the point at which the summed moment of all points in the cloud was zero) was then calculated in the x-, y- and z-directions (i.e., $x_{CoM}$, $y_{CoM}$, $z_{CoM}$) using the following equations:

$$x_{CoM} = \sum_{k=0}^{n} \frac{m_k . x_K}{M_{Total}} \quad \text{Equation 1}$$

$$y_{CoM} = \sum_{k=0}^{n} \frac{m_k . y_K}{M_{Total}} \quad \text{Equation 2}$$

$$z_{CoM} = \sum_{k=0}^{n} \frac{m_k . z_K}{M_{Total}} \quad \text{Equation 3}$$

Where $M_{Total}$ is the mass of the participant, n is the number of points in the 'clean' point cloud, $m_k$ is the mass of each point averaged across the surface (i.e., mass of the participant / number of points) and $x_k$, $y_k$ and $z_k$ are global (i.e., transformed) coordinates of individual points (Figure 1aii).

*Data processing:* The displacement data from both systems were differentiated to yield velocities and accelerations. All data were then time-normalised to a percentage of the jump cycle (Figure 1b), using the first (20% of jump cycle) and second trough (55% of jump cycle) of the $z_{CoM}$ time-series data as anchor points (shown as dashed line in Figure 1ai, Sagittal View). The normalised data in the y-direction (anterior-posterior) were processed to yield outcome measures of jump performance, which were: displacement of the feet (cm) defined as the distance between the right and left foot markers at 20% and 55%, respectively; displacement of the CoM (cm) defined as the distance between 20% and 55%; peak velocity and acceleration defined as the highest positive velocity ($m \cdot s^{-1}$) and acceleration ($m \cdot s^{-2}$) in the y-direction throughout the cycle.

*Statistical Analysis:* Since our aims are to assess the agreement between two measurement systems, rather than to examine any biological outcomes, data from all participants (n = 14) and their trials (n = 10 pp) were treated as independent measures (i.e., n = 140 datapoints per outcome measure). We used separate linear regressions (SPSS Version 24, IBM Corp., Armonk, NY, USA) to examine the criterion-related validity of the foot displacement and whole-body COM kinematics. Criterion-derived values of the outcome measures were entered as separate dependent variables and the corresponding PCP-derived values were entered as independent variables. Relationship strength was quantified with Pearson's product moment correlation coefficient (*r*), with the associated $R^2$ value (coefficient of determination) used to express the proportion of explained variance. Additionally, the intraclass correlation coefficient was calculated using a two-way mixed effects model ($ICC_{3,1}$), but these are not reported given that the values were all within ±0.0002 of the Pearson's *r* for displacement and velocity and ±0.0274 for accelerations. Typical errors ([TE], or standard errors of the estimate) were used to represent unexplained (random) bias. The mean difference between PCP and the criterion was used to represent systematic (mean) bias. Finally, Bland & Altman's 95% limits of agreement were calculated by adding and subtracting 1.96 times the standard deviation of the difference (PCP–criterion) in paired measurements (Bland and Altman, 1986).

Uncertainty in all estimates were expressed using 90% confidence limits (CL), calculated from the *t*-distribution for mean differences, the *z*-distribution for (transformed) correlation coefficients and the chi-squared distribution for SEE. We declared the magnitude of correlation coefficients as small moderate, large, very large and near perfect based on standardized anchors of 0.1, 0.3, 0.5, 0.7 and 0.9, respectively (Hopkins et al., 2009). To provide a standardised interpretation of mean bias (i.e., *d*), we used 0.2, 0.6 and 1.2 of the pooled between-participant standard deviation for each outcome measure (Table 1) to represent small, moderate and large differences (Hopkins et al., 2009). These thresholds were then halved to declare practical magnitudes of SEEs (Smith & Hopkins, 2011). We relied on subjective interpretation of the entire CL (i.e., lower and upper limits) against these thresholds to communicate effect magnitude.

## Results

Between 0 to 20% of the jump cycle, the CoM moves laterally to above the position of the standing foot and then in a shallow countermovement (i.e., trunk, hip, knee and ankle flexion) the z-position of the CoM falls (Figure 1ai). At the same time, the athlete begins to shift the CoM anteriorly relative to the base of support, thus creating anterior misalignment between the COM and base of support. The athlete is then able to move CoM horizontally (Figure 1bi) during the push-off (20-30%) by extending the joints. The peak velocity of the CoM in the y-direction occurs between 30 and 40% of the cycle (Figure 1bii) and the CoM is decelerated abruptly thereafter (Figure 1biii). The athlete attempts to control the CoM above the base of support provided by the landed foot and hold this position until the end of the trial. There was general agreement between the systems for all three kinematic variables in the y-direction, although the PCP tended to overestimate positive accelerations during take-off and underestimate the negative accelerations during landing (Figure 1biii).

The results of the validity analysis are shown in Table 1 and Figure 1c. The association (*r*) between the systems for outcome measures were near perfect for foot displacement, CoM displacement and peak velocity, and very large for peak acceleration. Mean biases were trivial for total foot displacement (<0.2%) and CoM peak velocity (~1.5%), CoM total displacement (3.5%), and small for CoM peak acceleration (~7%). The typical errors were trivial for total foot displacement (~1%), small for total CoM displacement (~3.5%) and CoM peak velocity (~4%), and large for CoM peak acceleration (~15%). The limits of agreement (Figure 1c) for foot displacement (-1.9cm to 2.0cm), CoM displacement (-11.3cm to 3.6cm), CoM peak velocity (-0.17 to 0.12$m \cdot s^{-1}$) and CoM peak acceleration (-2.28 to 1.43$m \cdot s^{-2}$).

## Discussion

Biomechanical analysis of movement screening tests could play an important role in both athletic and clinical settings. In these areas, expediency and validity are highly valued. Despite its simplicity, the PCP-system showed excellent criterion validity with a 3D motion analysis system in tracking whole-body CoM and feet markers simultaneously during a single-legged horizontal jump. Typical errors between the systems in foot displacements were 0.94 cm (< 1%) which are considered acceptable in field-testing (Mccubine et al., 2017). The errors in CoM displacement were 3.8 cm, being similar to other practical measures used in gait research (3 cm, Yang and Pai, 2014; 4 cm Huntley et al., 2017), but slightly larger than those from inertial suits (2.6 cm, Fasel et al., 2017). A key advantage of the PCP over other technologies is the simplicity of data collection. Following a ten-minute setup, the system was able run continuously to capture and display outcome measures within 300ms of task completion. As a case in point, we lost approximately 10% of the trials due to issues regarding data collection, and these were all related to the criterion system.

As with most areas of biomechanics, an optimal trade-off may exist between practicality, accuracy and cost (Devetaka et al., 2019); this will depend largely on how accurate the system needs to be. Accordingly, we provided a more standardised interpretation of our findings for this task and found trivial mean biases for all outcome measures, with typical errors being trivial for displacement, small for velocity and large for accelerations. Furthermore, the 95% limits of agreement of foot displacement (-1.9 to 2.0 cm), for example, are small compared the variation of performance between young active adults (group standard deviations, male: 19.3; female: 12.8 cm) (Meylan et al., 2009). Our data therefore suggest that, although not perfect, both foot and CoM displacement may be quantified with acceptable precision to detect small but worthwhile changes. However, velocities and accelerations may need further work, and this may entail different camera orientations, higher resolution, multiple cameras and/or higher sampling frequency.

There are important limitations to this study. First, the current single camera was only able to capture at 30Hz, a possible reason for the only large typical error for peak accelerations (~15%). Further improvements such as higher sampling or multiple cameras may be required to quantify acceleration-based CoM variables. Second, we did not collect data using different camera placements relative to the movements. Recent findings, reveal that the data from such low-cost cameras are sensitive to camera viewing angle (Yeung et al., 2021) and further work to optimise orientation may assist in reducing errors shown in the current study. Third, our sample was quite homogeneous in terms of sex and training status; thus, the accuracy of the system may need to be tested in other populations. Further work using female and/or highly trained (elite) athletes may produce different results, possibly susceptible to different body compositions and/or different kinematics during jump tasks. Further examination of validity in different populations may still be necessary. Fourth, we have not modelled all possible performance outcomes related to the foot and CoM relationship: it is not known how these errors propagate when other measures, such as dynamic balance (Hrysomallis, 2011), are calculated.

## Conflict of interest statement

At the time of this research, IS and MP were providing consultancy support to Pro Sport Support Ltd—a company seeking the development and commercial sale of practical, marker-based tracking systems for athletic movement screening. The PCP-based system for assessing horizontal jumps forms part of an athlete assessment tool (AMAT Performance, Pro Sport Support Ltd, UK) and is currently in use in football academies (Laas et al., 2020).

## Funding Sources

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## Figure Legends

Figure 1.

a) Schematic representation of the capture setup (i) used by the two systems to capture concurrently the movements of athlete during a single-legged jump (right to left). Also shown is the global origin (0,0,0) of the criterion system and the rigid calibration frame (P1, P2, P3 and P4). Jumping was performed in the positive y-direction (anterior) towards the low-cost camera. In the sagittal view (lower image), the ‘clean’ point cloud along with the trajectories of the whole-body CoM (long-dashed line) and the left foot marker (short-dashed line) are shown. Note the two localised minima of the y-position of the whole-body CoM that were used to anchor the data from the two systems (20% and 55% of the jump cycle). Also shown are the ‘clean’ point clouds in frontal view (z-x plane) in colour (ii) and infrared (iii). The calculation of whole-body CoM uses all these points, whereas calculation of foot marker position uses only the point at the virtual midpoint between the 2 strips of reflective (highlighted with a cross on the infrared image (iii).

b) Time-normalised kinematics from Vicon (blue) and PCP (yellow) (mean ± SD) for the CoM in the y-direction (n= 1200) are shown. Overlapping regions of the standard deviations are shown in green. Note that all y-axes are scaled to span the range between maximal and minimal data points on the time-series.

c) Limits of agreements (Bland and Altman,1986) for the two systems (±1.96SD) for foot displacement (i), CoM displacement (ii), CoM peak velocity (iii) and CoM peak acceleration (iv).

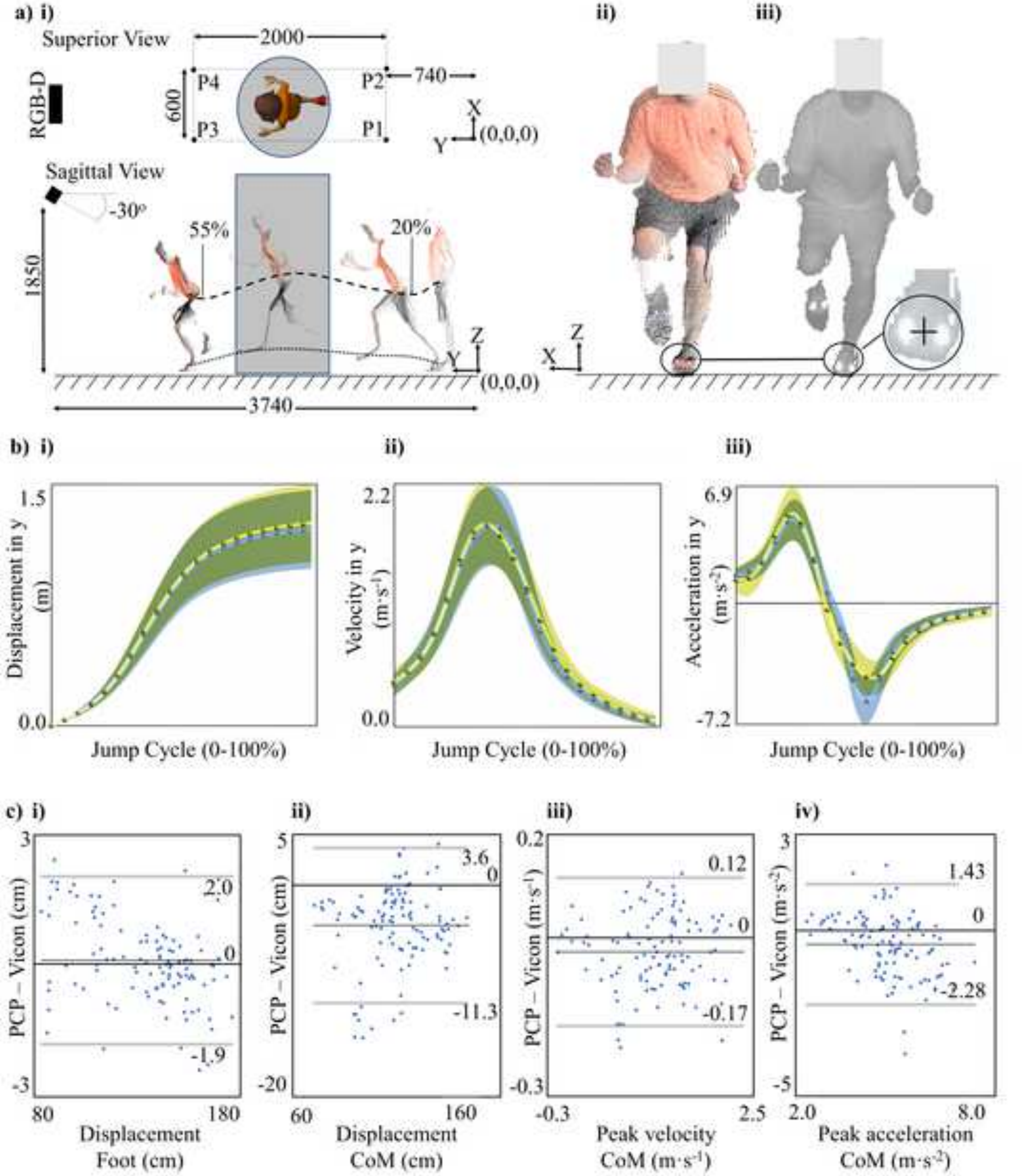
a) i)
Superior View
RGB-D
2000
600
P4
P3
P2
P1
740
X
Y
(0,0,0)
Sagittal View
-30º
1850
55%
20%
Z
Y
(0,0,0)
3740
ii)
iii)
Z
X
b) i)
1.5
0.0
Displacement in y (m)
Jump Cycle (0-100%)
ii)
2.2
0.0
Velocity in y (m·s-1)
Jump Cycle (0-100%)
iii)
6.9
-7.2
Acceleration in y (m·s-2)
Jump Cycle (0-100%)
c) i)
3
-3
2.0
0
-1.9
PCP – Vicon (cm)
80
180
Displacement Foot (cm)
ii)
5
-20
3.6
0
-11.3
PCP – Vicon (cm)
60
160
Displacement CoM (cm)
iii)
0.2
-0.3
0.12
0
-0.17
PCP – Vicon (m·s-1)
-0.3
2.5
Peak velocity CoM (m·s-1)
iv)
3
-5
1.43
0
-2.28
PCP – Vicon (m·s-2)
2.0
8.0
Peak acceleration CoM (m·s-2)

**Table 1.** Validity analysis between point-cloud processing (PCP) and criterion-derived estimates of jump performance during the single-leg jump

| **Outcome Measure** | **Performance* (mean ± SD)** | ***r* (±90% CL)*** | $R^2$ | **Mean bias (±90% CL)** | | **Typical Error (×/÷90% CL)** | |
|---|---|---|---|---|---|---|---|
| | | | | **Raw Units** | **Standardized (*d*)**[a] | **Raw Units** | **Standardized (*d*)**[b] |
| Total Foot Displacement (cm) | 140.5 ± 27.2 | 0.999; ±0.0002 | 0.999 | -0.07 (0.15) | 0.00 (0.01) | 0.92 (1.12) | 0.03 (1.17) |
| Total CoM Displacement (cm) | 126.5 ± 21.2 | 0.983; ±0.005 | 0.967 | 3.84 (0.6) | 0.18 (0.03) | 3.83 (1.12) | 0.18 (1.17) |
| CoM Peak Velocity (m·s$^{-1}$) | 1.84 ± 0.30 | 0.973; ±0.009 | 0.946 | 0.03 (0.01) | 0.09 (0.04) | 0.07 (1.12) | 0.24 (1.18) |
| CoM Peak Acceleration (m·s$^{-2}$) | 5.49 ± 1.46 | 0.792; ±0.059 | 0.627 | 0.42 (0.15) | 0.38 (0.13) | 0.72 (1.12) | 0.86 (1.23) |

*from the PCP

[a] < 0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, >1.2 = large.

[b] < 0.1 = trivial, 0.1–0.3 = small, 0.3–0.6 = moderate, >0.6 = large.

CL, confidence limits.

## Conflict of interest statement

At the time of this research, IS and MP were providing consultancy support to Pro Sport Support Ltd—a company seeking the development and commercial sale of practical, marker-based tracking systems for athletic movement screening. The novel PCP-based system for assessing horizontal jumps forms part of an athlete assessment tool (AMAT Performance, Pro Sport Support Ltd, UK) and is currently in use in football academies (Laas et al., 2020).

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