Dual Kinect v2 system can capture lower limb kinematics reasonably well in a clinical setting: concurrent validity of a dual camera markerless motion capture system in professional football players

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ABSTRACT

Objectives To determine whether a dual-camera markerless motion capture system can be used for lower limb kinematic evaluation in athletes in a preseason screening setting.

Design Descriptive laboratory study.

Setting Laboratory setting.

Participants Thirty-four (n=34) healthy athletes.

Main outcome measures Three-dimensional lower limb kinematics during three functional tests: Single Leg Squat (SLS), Single Leg Jump, Modified Counter-movement Jump. The tests were simultaneously recorded using both a marker-based motion capture system and two Kinect v2 cameras using iPi Mocap Studio software.

Results Excellent agreement between systems for the flexion/extension range of motion of the shin during all tests and for the thigh abduction/adduction during SLS were seen. For peak angles, results showed excellent agreement for knee flexion. Poor correlation was seen for the rotation movements.

Conclusions This study supports the use of dual Kinect v2 configuration with the iPi software as a valid tool for assessment of sagittal and frontal plane hip and knee kinematic parameters but not axial rotation in athletes.

INTRODUCTION

Precompetition medical assessment of athletes commonly includes assessment of movement quality while athletes perform standardised testing procedures. Depending on the particular sport's performance requirements and injury patterns, different test batteries are employed in an effort to identify at-risk individuals to target for tailored interventions. The quantification of these movement assessment tests is typically performed with simple visual analysis and rating,1 or occasionally using video recording and later 2-dimensional analysis. Such approaches have shown limited accuracy in estimating injury likelihood, and it has been suggested that this could be attributed, in part, to the reduced objectivity of these approaches in comparison to 3-dimensional kinematic analyses.

In the context of football (soccer), commonly performed functional tests include: Single Leg Squat (SLS) assessing movement in frontal plane knee motion;2-4 Single Leg Jump (SLJ)3,4, and Counter-movement Jump (CMJ) for lower limb power estimation.5 Additionally, a modification of the CMJ with the athlete landing on one leg instead of two (Modified Counter Movement Jump (MCMJ)) has been recommended as being more sport-specific.8

Marker-based motion capture is currently considered the reference method for kinematic analyses. These approaches, however, require expensive equipment, significant operator training and analysis time as well as increased subject set-up time. Accordingly, these approaches are rarely employed in settings where time and/or financial constraints exist such as preseason screening of athletes performing functional movement. Additionally, these somewhat artificial laboratory conditions can cause unknown experimental artefacts.9

Recent advances and improved access to markerless motion capture technology have
made the use of low-cost motion analysis tools a possibility in the clinical setting. However, the validity of this technology in more complex functional movements is currently unclear. The majority of studies done so far used Kinect v1, one camera and the Software Development Kit (SDK) provided by Microsoft. Researchers have evaluated the configuration during working activities, gait in healthy population, gait in multiple-sclerosis, and after cerebrovascular accident, and during a jump test. More recently, single Kinect v2 was used with Microsoft SDK to test the validity during gait and for balance. A multi-Kinect v2 configuration with Microsoft SDK was tested for its validity during gait. To our knowledge, until now, no validation of a dual-camera markerless system during dynamic, advanced movements has been done.

The goals of this study were to examine the validity of a markerless motion capture system using 2 Kinect v2 cameras with custom software during functional movements commonly performed during pre-season physical screening evaluation.

METHOD

Participants

Thirty-four pain-free male professional football players participated in the study (table 1). All athletes had no previous lower extremity surgery and no current injury. We followed Fleiss’ recommendation for reliability studies after considering previous work in the area.

Table 1 Participant information

| Participants | Mean±SD     |
|--------------|-------------|
| Age (years)  | 26.63 (±4.23) |
| Weight (kg)  | 73.58 (±11.44) |
| Height (cm)  | 176.01 (±8.01) |
| BMI (kg/m²)  | 23.62 (±2.25) |

BMI, body mass index.

Materials

Marker trajectories were measured with a 13-camera motion capture system (BTS-SMART 1000, BTS S.p.A., Italy) sampling at 250 Hz. Depth and colour image data were simultaneously recorded with 2 Kinect v2 cameras at 30 Hz (Kinect for Windows, Microsoft, Redmond, Washington, USA) and iPi Recorder (iPi Soft, Moscow, Russia). Kinect cameras were placed one in front and one to the left side of the capture area (in between the 2 Optojump sensors) at an angle of 70° between them (figure 1).

Data collection

After warm up for a minimum of 5 min, 31 markers were placed using clusters for thigh and shin and on anatomical landmarks according to standard marker protocol (figure 2). Participants stood in the capture area and performed three repetitions each of a SLS, a SLJ and a MCMJ, in the same order. Each trial was captured from BTS and Kinect cameras simultaneously.

Data analysis

Kinematic data from the Kinect cameras were processed using biomechanics add-on software (iPi Soft, Moscow, Russia). Marker trajectories from the marker-based system were processed using the SMART Analyser application (BTS S.p.A., Italy). For this analysis, the trajectories were adjusted to iPi Software such that comparison of the extracted data could be made. Marker based data were filtered using Butterworth Low Pass Filter at 6 Hz and resampled at 30 Hz. Kinematic data from both systems were extracted in Euler angles (rotation sequence XYZ),
Table 2  Range of angles, averaged over the three cycles during the Single Leg Squat test for BTS (considered as reference standard) and IPI software-Kinect configuration

| Test       | Segment Movement | System  | Mean (SD) | 95% CI     | ICC(2,k) (95% CI) | P value | SEM (deg) | MDC (deg) |
|------------|------------------|---------|-----------|------------|-------------------|---------|-----------|-----------|
| SLS_L (n=34) | THIGH            | BTS     | 42.5 (6.5) | 40.2 - 44.7 | 0.532 (-0.21 to 0.84) | 0.000   | 3.8       | 10.5      |
|            |                  | iPi     | 52.6 (7.8) | 49.8 - 55.3 |                     |         |           |           |
| Rotation   |                  | BTS     | 15.1 (3.2) | 14.0 - 16.2 | 0.312 (-0.31 to 0.65) | 0.069   | 3.5       | 9.6       |
|            |                  | iPi     | 13.5 (4.5) | 12.0 - 15.1 |                     |         |           |           |
| Abduction/Adduction | BTS | 13.2 (4.7) | 11.6 - 14.9 | 0.775 (0.55 to 0.89) | 0.791   | 3.4       | 9.5       |
|            |                  | iPi     | 13.5 (6.4) | 11.2 - 15.7 |                     |         |           |           |
| SHIN       | Flexion/Extension| BTS     | 26.3 (5.3) | 24.4 - 28.1 | 0.886 (0.73 to 0.95) | 0.006   | 2.4       | 6.7       |
|            |                  | iPi     | 28.0 (6.2) | 25.8 - 30.2 |                     |         |           |           |
| Rotation   |                  | BTS     | 21.0 (4.4) | 19.5 - 22.5 | 0.126 (-0.31 to 0.47) | 0.000   | 4.7       | 12.9      |
|            |                  | iPi     | 15.5 (5.4) | 13.6 - 17.4 |                     |         |           |           |
| Abduction/Adduction | BTS | 15.5 (6.7) | 13.1 - 17.8 | 0.718 (0.17 to 0.88) | 0.000   | 3.4       | 9.4       |
|            |                  | iPi     | 11.5 (5.2) | 9.7 - 13.3  |                     |         |           |           |
| FOOT       | Flexion/Extension| BTS     | 4.7 (4.0)  | 3.3 - 6.0   | 0.324 (-0.20 to 0.68) | 0.000   | 3.1       | 8.6       |
|            |                  | iPi     | 12.2 (4.6) | 10.6 - 13.8 |                     |         |           |           |
| Rotation   |                  | BTS     | 2.4 (1.8)  | 1.7 - 3.0   | 0.084 (-0.09 to 0.32) | 0.000   | 2.6       | 7.2       |
|            |                  | iPi     | 11.5 (3.8) | 10.2 - 12.8 |                     |         |           |           |
| Abduction/Adduction | BTS | 11.2 (4.1) | 9.8 - 12.7  | 0.867 (0.73 to 0.93) | 0.000   | 2.1       | 6.0       |
|            |                  | iPi     | 11.4 (4.7) | 9.8 - 13.1  |                     |         |           |           |
| SLS_R (n=34) | THIGH            | BTS     | 43.0 (10.6)| 39.3 - 46.7 | 0.604 (-0.13 to 0.88) | 0.000   | 3.9       | 10.7      |
|            |                  | iPi     | 57.1 (9.6) | 53.7 - 60.4 |                     |         |           |           |
| Rotation   |                  | BTS     | 13.9 (4.3) | 12.4 - 15.4 | 0.515 (0.01 to 0.76) | 0.891   | 3.4       | 9.4       |
|            |                  | iPi     | 14.0 (4.0) | 12.6 - 15.4 |                     |         |           |           |
| Abduction/Adduction | BTS | 16.1 (7.6) | 13.4 - 18.7 | 0.758 (0.52 to 0.88) | 0.134   | 4.1       | 11.4      |
|            |                  | iPi     | 17.6 (5.6) | 15.7 - 19.6 |                     |         |           |           |
| SHIN       | Flexion/Extension| BTS     | 26.3 (5.7) | 24.3 - 28.3 | 0.854 (0.70 to 0.93) | 0.051   | 3.1       | 8.5       |
|            |                  | iPi     | 27.8 (6.9) | 25.4 - 30.2 |                     |         |           |           |
| Rotation   |                  | BTS     | 20.2 (4.4) | 18.7 - 21.8 | -0.210 (-0.76 to 0.26) | 0.000   | 4.7       | 13.0      |
|            |                  | iPi     | 14.1 (4.1) | 12.6 - 15.5 |                     |         |           |           |
| Abduction/Adduction | BTS | 16.5 (9.3) | 13.3 - 19.7 | 0.319 (-0.18 to 0.63) | 0.000   | 6.2       | 17.1      |
|            |                  | iPi     | 10.1 (4.1) | 8.7 - 11.5  |                     |         |           |           |
| FOOT       | Flexion/Extension| BTS     | 5.7 (2.7)  | 4.7 - 6.6   | 0.079 (-0.28 to 0.41) | 0.000   | 4.0       | 11.0      |
|            |                  | iPi     | 11.1 (5.2) | 9.3 - 12.9  |                     |         |           |           |
| Rotation   |                  | BTS     | 2.2 (1.9)  | 1.5 - 2.9   | 0.102 (-0.10 to 0.36) | 0.000   | 1.9       | 5.2       |
|            |                  | iPi     | 8.4 (2.4)  | 7.6 - 9.2   |                     |         |           |           |
| Abduction/Adduction | BTS | 10.2 (2.9) | 9.2 - 11.2  | 0.707 (0.42 to 0.85) | 0.070   | 2.2       | 6.0       |
|            |                  | iPi     | 11.2 (3.6) | 9.9 - 12.5  |                     |         |           |           |

ICC(2,k), intraclass correlation coefficient (absolute agreement); MDC, minimal detectable change calculated as SEMx1.96x√2. P<0.05; SEM, SE of the measure calculated as the square root of the residual mean square; SLS_L, Single Leg Squat Left; SLS_R, Single Leg Squat Right.

in degrees, relative to the ground for thigh, shin and foot. For each trial, time synchronisation was performed manually by identifying the starting point of each trial as the moment of heel raise from the floor and the end point as the moment of heel contact to the floor.

The range of movement at the thigh, shin and foot and peak angles at the thigh and shin were averaged across three cycles in each exercise and used for subsequent analysis. Range of movement was calculated for each joint of interest as the difference between...
### Table 3  
Range of angles, averaged over the three cycles during the Single Leg Jump test for BTS (considered as reference standard) and IPI software-Kinect configuration

| Test          | Segment Movement | System | Mean (SD) | 95% CI       | ICC(2,k) (95% CI) | P value | SEM | MDC |
|---------------|------------------|--------|-----------|---------------|-------------------|---------|-----|-----|
| SLJ_L (n=31)  | THIGH            | BTS    | 39.0 (9.2)| 35.6 to 42.3 | 0.491 (-0.17 to 0.82) | 0.000   | 4.4 | 12.3 |
|               |                  | iPi    | 52.5 (7.9)| 49.6 to 55.4 |                    |         |     |     |
|               | Rotation         | BTS    | 21.6 (6.5)| 19.5 to 23.8 | 0.622 (0.21 to 0.82) | 0.870   | 4.7 | 13.0 |
|               |                  | iPi    | 21.8 (6.6)| 19.4 to 24.3 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 22.2 (8.6) | 19.0 to 25.3 | 0.462 (-0.09 to 0.74) | 0.216 | 5.7 | 15.9 |
|               |                  | iPi    | 20.3 (4.5) | 18.7 to 22.0 |                    |         |     |     |
| SHIN          | Flexion/Extension | BTS   | 28.9 (7.5) | 26.1 to 31.6 | 0.816 (0.62 to 0.91) | 0.084   | 3.6 | 9.9  |
|               |                  | iPi    | 27.2 (5.4) | 25.2 to 29.2 |                    |         |     |     |
|               | Rotation         | BTS    | 29.0 (4.9) | 27.2 to 30.8 | -0.260 (-0.94 to 0.28) | 0.000   | 6.0 | 16.5 |
|               |                  | iPi    | 22.2 (6.0) | 20.0 to 24.3 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 19.2 (4.4) | 17.6 to 20.8 | 0.529 (-0.20 to 0.84) | 0.000   | 2.2 | 6.1  |
|               |                  | iPi    | 13.2 (4.0) | 11.8 to 14.7 |                    |         |     |     |
| FOOT          | Flexion/Extension | BTS   | 41.6 (10.0)| 38.0 to 45.3 | 0.487 (-0.13 to 0.82) | 0.000   | 4.2 | 11.7 |
|               |                  | iPi    | 26.4 (7.9) | 23.5 to 29.3 |                    |         |     |     |
|               | Rotation         | BTS    | 15.0 (4.3) | 13.4 to 16.6 | 0.461 (-0.04 to 0.73) | 0.010   | 4.3 | 11.9 |
|               |                  | iPi    | 18.0 (6.1) | 15.8 to 20.2 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 23.3 (4.5) | 21.6 to 25.0 | 0.213 (-0.18 to 0.55) | 0.000   | 3.6 | 10.1 |
|               |                  | iPi    | 15.1 (4.3) | 13.5 to 16.7 |                    |         |     |     |
| SLJ_R (n=33)  | THIGH            | BTS    | 39.3 (9.1) | 36.0 to 42.5 | 0.658 (-0.19 to 0.88) | 0.000   | 4.5 | 12.3 |
|               |                  | iPi    | 47.4 (7.5) | 44.7 to 50.1 |                    |         |     |     |
|               | Rotation         | BTS    | 21.2 (5.3) | 19.3 to 23.1 | 0.563 (0.15 to 0.78) | 0.063   | 3.8 | 10.5 |
|               |                  | iPi    | 19.4 (4.5) | 17.8 to 21.0 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 17.1 (5.3) | 15.2 to 19.0 | 0.725 (0.44 to 0.86) | 0.036   | 3.2 | 8.8  |
|               |                  | iPi    | 15.4 (4.6) | 13.8 to 17.0 |                    |         |     |     |
| SHIN          | Flexion/Extension | BTS   | 27.9 (8.9) | 24.8 to 31.1 | 0.926 (0.84 to 0.96) | 0.022   | 3.0 | 8.4  |
|               |                  | iPi    | 26.1 (8.3) | 23.2 to 29.1 |                    |         |     |     |
|               | Rotation         | BTS    | 29.2 (5.3) | 27.3 to 31.1 | 0.297 (-0.21 to 0.63) | 0.000   | 4.1 | 11.3 |
|               |                  | iPi    | 21.6 (4.9) | 19.9 to 23.4 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 16.7 (4.6) | 15.1 to 18.3 | 0.780 (-0.16 to 0.94) | 0.000   | 1.9 | 5.2  |
|               |                  | iPi    | 12.8 (5.0) | 11.0 to 14.6 |                    |         |     |     |
| FOOT          | Flexion/Extension | BTS   | 43.1 (9.9) | 39.6 to 46.7 | 0.443 (-0.10 to 0.80) | 0.000   | 4.4 | 12.1 |
|               |                  | iPi    | 24.5 (9.7) | 21.0 to 27.9 |                    |         |     |     |
|               | Rotation         | BTS    | 14.4 (4.3) | 12.9 to 15.9 | 0.421 (-0.11 to 0.71) | 0.000   | 3.3 | 9.2  |
|               |                  | iPi    | 18.0 (4.0) | 16.6 to 19.5 |                    |         |     |     |
|               | Abduction/Adduction | BTS | 21.7 (4.9) | 19.9 to 23.4 | 0.289 (-0.20 to 0.64) | 0.000   | 3.4 | 9.5  |
|               |                  | iPi    | 13.5 (4.2) | 12.0 to 15.0 |                    |         |     |     |

**Statistical analysis**

A two-way mixed analysis of variance (ANOVA) (absolute agreement) was performed to assess the reliability and the variability of the measurements. Between measurement agreement was assessed using intraclass correlation coefficient (ICC). SEM, SE of the measure calculated as the square root of the residual mean square; SLJ_L, Single Leg Jump Left; SLJ_R, Single Leg Jump Right.

maximum and minimum angles for each cycle. Mean subject-based values for each test were then determined. Note that these were calculated independently for both the markerless (Kinect) and marker-based (BTS) equipment.
## Table 4  Range of angles, averaged over the three cycles during the modified counter movement test for BTS (considered as reference standard) and IPI software-Kinect configuration

| Test       | Segment  | Movement            | System | Mean (SD)   | 95% CI          | ICC(2,k) (95% CI) | P value | SEM (deg) | MDC (deg) |
|------------|----------|---------------------|--------|-------------|----------------|------------------|---------|-----------|-----------|
| MCMJ_L     | THIGH    | Flexion/Extension   | BTS    | 59.8 (10.4) | 56.1 to 63.5   | 0.851 (0.07 to 0.95) | 0.000    | 3.5       | 9.8       |
|            |          |                     | iPi    | 65.7 (9.3)  | 62.4 to 69.0   |                  |         |           |           |
|            |          | Rotation            | BTS    | 26.1 (7.3)  | 23.5 to 28.7   | 0.518 (0.00 to 0.77) | 0.000    | 4.7       | 13.0      |
|            |          |                     | iPi    | 21.4 (5.1)  | 19.6 to 23.2   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 26.9 (5.8)  | 24.8 to 28.9   | 0.644 (0.23 to 0.83) | 0.002    | 5.6       | 15.5      |
|            |          |                     | iPi    | 31.6 (10.2) | 28.0 to 35.2   |                  |         |           |           |
| SHIN       |          | Flexion/Extension   | BTS    | 35.1 (5.8)  | 33.1 to 37.2   | 0.801 (0.60 to 0.90) | 0.578    | 3.4       | 9.5       |
|            |          |                     | iPi    | 34.7 (6.1)  | 32.5 to 36.8   |                  |         |           |           |
|            |          | Rotation            | BTS    | 35.7 (9.5)  | 32.3 to 39.1   | 0.571 (0.05 to 0.80) | 0.000    | 5.8       | 16.1      |
|            |          |                     | iPi    | 29.7 (6.7)  | 27.3 to 32.1   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 19.6 (5.2)  | 17.8 to 21.4   | 0.493 (−0.05 to 0.75) | 0.000    | 3.2       | 8.8       |
|            |          |                     | iPi    | 16.1 (2.9)  | 15.1 to 17.1   |                  |         |           |           |
| FOOT       |          | Flexion/Extension   | BTS    | 47.8 (10.8) | 44.0 to 51.7   | 0.384 (−0.13 to 0.75) | 0.000    | 5.2       | 14.3      |
|            |          |                     | iPi    | 28.7 (8.1)  | 25.9 to 31.6   |                  |         |           |           |
|            |          | Rotation            | BTS    | 22.4 (10.4) | 18.7 to 26.1   | 0.799 (0.59 to 0.90) | 0.053    | 4.8       | 13.2      |
|            |          |                     | iPi    | 24.8 (6.0)  | 22.6 to 26.9   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 23.9 (5.6)  | 21.9 to 25.9   | 0.550 (−0.23 to 0.83) | 0.000    | 2.8       | 7.7       |
|            |          |                     | iPi    | 18.3 (3.5)  | 17.0 to 19.5   |                  |         |           |           |
| MCMJ_R     | THIGH    | Flexion/Extension   | BTS    | 56.8 (11.2) | 53.0 to 60.7   | 0.765 (−0.19 to 0.93) | 0.000    | 3.9       | 10.9      |
|            |          |                     | iPi    | 66.3 (10.0) | 62.8 to 69.8   |                  |         |           |           |
|            |          | Rotation            | BTS    | 23.3 (4.7)  | 21.7 to 25.0   | −0.280 (−1.55 to 0.36) | 0.253    | 5.8       | 15.9      |
|            |          |                     | iPi    | 21.7 (6.1)  | 19.6 to 23.8   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 28.5 (5.8)  | 26.4 to 30.5   | 0.657 (0.33 to 0.83) | 0.059    | 5.0       | 13.8      |
|            |          |                     | iPi    | 26.1 (8.2)  | 23.2 to 29.0   |                  |         |           |           |
| SHIN       |          | Flexion/Extension   | BTS    | 33.7 (5.2)  | 31.9 to 35.5   | 0.856 (0.71 to 0.93) | 0.887    | 3.0       | 8.2       |
|            |          |                     | iPi    | 33.8 (6.4)  | 31.5 to 36.0   |                  |         |           |           |
|            |          | Rotation            | BTS    | 35.4 (6.3)  | 33.2 to 37.6   | 0.049 (−0.50 to 0.45) | 0.001    | 6.0       | 16.5      |
|            |          |                     | iPi    | 30.0 (5.8)  | 28.0 to 32.1   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 21.9 (7.0)  | 19.5 to 24.3   | −0.030 (−0.50 to 0.36) | 0.000    | 5.4       | 14.9      |
|            |          |                     | iPi    | 15.8 (2.9)  | 14.8 to 16.8   |                  |         |           |           |
| FOOT       |          | Flexion/Extension   | BTS    | 46.0 (8.6)  | 43.0 to 49.0   | 0.202 (−0.13 to 0.55) | 0.000    | 5.9       | 16.3      |
|            |          |                     | iPi    | 26.5 (7.1)  | 24.0 to 29.0   |                  |         |           |           |
|            |          | Rotation            | BTS    | 20.9 (4.0)  | 19.5 to 22.2   | 0.277 (−0.22 to 0.60) | 0.000    | 4.5       | 12.5      |
|            |          |                     | iPi    | 25.5 (6.1)  | 23.4 to 27.6   |                  |         |           |           |
|            |          | Abduction/Adduction | BTS    | 25.4 (4.9)  | 23.7 to 27.1   | 0.238 (−0.17 to 0.58) | 0.000    | 4.5       | 12.5      |

ICC(2,k), intraclass correlation coefficient (absolute agreement); MCMJ_L, Modified Counter-Movement Jump Left; MCMJ_R, Modified Counter-Movement Jump Right; MDC, minimal detectable change calculated as SEMx1.96x√2. P<0.05; SEM, standard error of the measure calculated as the square root of the residual mean square.

Coefficients (ICC) (2, k; absolute agreement). Because the ICC does not allow us to fully appreciate the magnitude of within-subject variance, we also calculated the SE of measurement (SEM) and the minimal detectable change (MDC).24 SEM represents the within-subject reliability of the measure and, consequently, the reliability of the measure.24 The SEM was determined as √MSE, where MSE=mean square error from the ANOVA table. The MDC represents the threshold over which an individual change can be considered meaningful when taking into account the variability associated with both the measurement technique and the experimental sample and was
Table 5  Peak angles averaged over the three cycles during the Single Leg Squat test for BTS (considered as reference standard) and IPI software-Kinect configuration

| Test          | Movement      | System     | Mean (SD) (deg) | 95% CI | ICC(2,k) (95% CI) | P value | SEM (deg) | MDC (deg) |
|---------------|---------------|------------|----------------|--------|------------------|---------|-----------|-----------|
| SLS_L (n=34)  | Hip flexion   | BTS        | −30.3 (17.5)   | −36.4  | −24.2            | 0.896   | −0.09     | 0.97      | 0.000     | 4.1       | 11.3     |
|               |               | iPi        | −40.6 (18.0)   | −46.9  | −34.3            |         |           |           |           |           |          |
|               | Hip adduction | BTS        | −18.6 (5.5)    | −20.6  | −16.7            | 0.749   | 0.49      | 0.88      | 0.029     | 3.3       | 9.2      |
|               |               | iPi        | −20.5 (5.4)    | −22.4  | −18.6            |         |           |           |           |           |          |
|               | Knee flexion  | BTS        | 30.0 (8.6)     | 27.0   | 33.0             | 0.932   | 0.71      | 0.98      | 0.000     | 2.5       | 6.8      |
|               |               | iPi        | 32.8 (8.5)     | 29.8   | 35.7             |         |           |           |           |           |          |
|               | Knee adduction| BTS        | −17.5 (6.1)    | −19.6  | −15.3            | 0.830   | 0.57      | 0.92      | 0.001     | 2.6       | 7.3      |
|               |               | iPi        | −15.3 (4.5)    | −16.8  | −13.7            |         |           |           |           |           |          |
| SLS_R (n=34)  | Hip flexion   | BTS        | −49.1 (14.8)   | −54.3  | −44.0            | 0.767   | −0.12     | 0.94      | 0.000     | 3.9       | 10.9     |
|               |               | iPi        | −63.9 (14.7)   | −69.0  | −58.7            |         |           |           |           |           |          |
|               | Hip adduction | BTS        | 22.8 (4.7)     | 21.1   | 24.4             | 0.684   | −0.13     | 0.89      | 0.000     | 2.6       | 7.2      |
|               |               | iPi        | 27.1 (5.1)     | 25.3   | 28.9             |         |           |           |           |           |          |
|               | Knee flexion  | BTS        | 25.9 (9.8)     | 22.5   | 29.4             | 0.947   | 0.83      | 0.98      | 0.001     | 2.8       | 7.8      |
|               |               | iPi        | 28.5 (10.7)    | 24.8   | 32.3             |         |           |           |           |           |          |
|               | Knee adduction| BTS        | 18.3 (5.8)     | 16.3   | 20.3             | 0.665   | 0.08      | 0.86      | 0.000     | 3.0       | 8.2      |
|               |               | iPi        | 14.7 (3.8)     | 13.4   | 16.1             |         |           |           |           |           |          |

ICC(2,k), intraclass correlation coefficient (absolute agreement); MDC, minimal detectable change calculated as SEM×1.96×√2. P<0.05; SEM, SE of the measure calculated as the square root of the residual mean square; SLS_L, Single Leg Squat Left; SLS_R, Single Leg Squat Right.

calculated using the equation MDC=1.96 × √2×SEM

Finally, to better understand system agreement of the peak joint angles, the 95% limits of agreement and the bias were calculated using Bland-Altman analysis. The bias represents the average difference in peak joint angle between the systems while the limits of agreement are the bias ±SD. Significance level was set at p<0.05. Correlation coefficients were interpreted as follows: less than 0.40 as poor, between 0.40 and 0.59 as fair, between 0.60 and 0.74 as good, between 0.75 and 1.00 as excellent. All analyses were performed using SPSS 23.0 (SPSS Statistics for Windows, V.23.0. Armonk, New York, USA: IBM).

RESULTS

Mean(±SD), absolute agreement ICC, SEM and MDC values for angles and ranges of motion are provided in tables 2–4.

Our results showed excellent between system agreement for shin movement in flexion/extension in all three tests, for both legs. Additionally, during the SLS test excellent agreement was found for thigh and foot adduction/abduction motion.

Results for peak angles are shown in tables 5–7. Between systems agreement was excellent for knee flexion in all tests for both legs.

Biases and limits of agreement (table 8) (online supplementary material 1: Bland-Altman plots) were documented. The mean differences are relatively low especially for hip adduction and knee flexion and adduction. For most of the measures examined, no systematic error is detected. For hip flexion, however, there appears to be a systematic error of approximately 10°.

DISCUSSION

Here, we have established, for the first time, validity values for SLS, CMJ and MCMJ in a cohort of professional athletes using a 2 camera markerless motion capture system (Kinect v2).

Our results indicate that a dual Kinect v2 configuration is a valid tool for assessment of sagittal plane knee range and peak angles, during squat and jumping tests. Additionally, during the SLS test excellent agreement between systems was found for thigh and foot adduction/abduction motion.

Although agreement improved when using two cameras configuration instead of one, the between system agreement varied widely, especially for movements of clinical interest like hip flexion, hip adduction and knee adduction. There was also variability in agreement for different joints and different parameters. For example, shin ab/adduction showed better reliability and validity when considering the peak values in comparison to the results from individual tests. Clinical interpretation is therefore recommended for each approach (eg, individual trials vs averaged values, vs peak values). It may be argued that, in the context of risk of an acute anterior cruciate ligament injury, the peak shin adduction is a more important metric than the average across a number of trials whereas in ‘overuse’ type injuries average values may be a more sensible estimator. Also, poor agreement was found...
### Table 6  Peak angles averaged over the three cycles during the Single Leg Jump test for BTS (considered the gold standard) and IPI software-Kinect configuration

| Test       | Movement | System | Mean (SD) | 95% CI | ICC(2,k) (95% CI) | P value | SEM | MDC |
|------------|----------|--------|-----------|--------|-------------------|---------|-----|-----|
|            |          |        | (deg)     | Lower (deg) | Upper (deg) |        |     |     |
| SLJ_L (n=31)| Hip flexion | BTS    | -27.1 (16.4) | -33.2 | -21.1 | 0.890 (-0.05 to 0.97) | 0.000 | 4.3 | 12.0 |
|            |          | iPi    | -36.6 (16.6) | -42.7 | -30.5 |                      |        |     |     |
|            | Hip adduction | BTS    | -19.0 (5.5) | -21.0 | -17.0 | 0.826 (0.64 to 0.92) | 0.744 | 2.9 | 7.9  |
|            |          | iPi    | -18.7 (4.9)  | -20.5 | -16.9 |                      |        |     |     |
|            | Knee flexion | BTS    | 31.4 (10.6)  | 27.5 | 35.3 | 0.951 (0.90 to 0.98) | 0.694 | 3.0 | 8.3  |
|            |          | iPi    | 31.7 (8.7)   | 28.5 | 34.9 |                      |        |     |     |
|            | Knee adduction | BTS    | -16.5 (4.9)  | -18.3 | -14.7 | 0.883 (0.32 to 0.96) | 0.000 | 1.7 | 4.7  |
|            |          | iPi    | -14.0 (5.0)  | -15.9 | -12.2 |                      |        |     |     |
| SLJ_R (n=33)| Hip flexion | BTS    | -46.8 (11.8) | -51.0 | -42.6 | 0.649 (-0.19 to 0.89) | 0.000 | 5.0 | 14.0 |
|            |          | iPi    | -60.7 (11.6) | -64.8 | -56.6 |                      |        |     |     |
|            | Hip adduction | BTS    | 23.1 (5.5)   | 21.2 | 25.0 | 0.901 (-0.04 to 0.97) | 0.002 | 3.7 | 10.2 |
|            |          | iPi    | 26.1 (5.9)   | 24.0 | 28.2 |                      |        |     |     |
|            | Knee flexion | BTS    | 27.5 (11.2)  | 23.6 | 31.5 | 0.956 (0.91 to 0.98) | 0.513 | 3.1 | 8.6  |
|            |          | iPi    | 28.1 (9.9)   | 24.5 | 31.6 |                      |        |     |     |
|            | Knee adduction | BTS    | 18.8 (4.9)   | 17.0 | 20.5 | 0.726 (-0.21 to 0.92) | 0.000 | 2.0 | 5.5  |
|            |          | iPi    | 14.3 (4.5)   | 12.6 | 15.9 |                      |        |     |     |

ICC(2,k), intraclass correlation coefficient (absolute agreement); MDC, minimal detectable change calculated as SEMx1.96x√2. P<0.05; SEM, SE of the measure calculated as the square root of the residual mean square; SLJ_L, Single Leg Jump Left; SLJ_R, Single Leg Jump Right.

### Table 7  Peak angles averaged over the three cycles during the modified counter movement test for BTS (considered the gold standard) and IPI software-Kinect configuration

| Test       | Movement | System | Mean (SD) | 95% CI | ICC(2,k) (95% CI) | P value | SEM | MDC |
|------------|----------|--------|-----------|--------|-------------------|---------|-----|-----|
|            |          |        | (deg)     | Lower (deg) | Upper (deg) |        |     |     |
| MCMJ_L (n=33)| Hip flexion | BTS    | -49.4 (18.7) | -56.0 | -42.8 | 0.947 (0.33 to 0.99) | 0.000 | 3.7 | 10.2 |
|            |          | iPi    | -56.3 (18.4) | -62.8 | -49.7 |                      |        |     |     |
|            | Hip adduction | BTS    | -18.8 (6.0)  | -20.9 | -16.7 | 0.792 (0.17 to 0.92) | 0.002 | 2.5 | 7.0  |
|            |          | iPi    | -15.3 (4.8)  | -17.1 | -13.6 |                      |        |     |     |
|            | Knee flexion | BTS    | 35.8 (10.1)  | 32.2 | 39.4 | 0.954 (0.80 to 0.98) | 0.000 | 2.4 | 6.6  |
|            |          | iPi    | 38.4 (9.7)   | 35.0 | 41.9 |                      |        |     |     |
|            | Knee adduction | BTS    | -16.3 (6.0)  | -18.5 | -14.2 | 0.873 (0.59 to 0.95) | 0.000 | 2.4 | 6.5  |
|            |          | iPi    | -13.9 (5.6)  | -15.9 | -12.0 |                      |        |     |     |
| MCMJ_R (n=34)| Hip flexion | BTS    | -65.7 (14.5) | -70.8 | -60.7 | 0.846 (-0.14 to 0.96) | 0.000 | 3.5 | 9.7  |
|            |          | iPi    | -76.4 (13.9) | -81.3 | -71.6 |                      |        |     |     |
|            | Hip adduction | BTS    | 24.0 (5.9)   | 21.9 | 26.0 | 0.713 (0.12 to 0.88) | 0.000 | 3.1 | 8.5  |
|            |          | iPi    | 20.1 (5.0)   | 18.4 | 21.9 |                      |        |     |     |
|            | Knee flexion | BTS    | 31.0 (8.3)   | 28.1 | 33.9 | 0.945 (0.81 to 0.98) | 0.000 | 2.5 | 6.8  |
|            |          | iPi    | 33.4 (9.6)   | 30.1 | 36.8 |                      |        |     |     |
|            | Knee adduction | BTS    | 16.8 (5.2)   | 15.0 | 18.6 | 0.742 (-0.01 to 0.91) | 0.000 | 2.5 | 6.9  |
|            |          | iPi    | 13.1 (4.8)   | 11.4 | 14.7 |                      |        |     |     |

ICC(2,k), intraclass correlation coefficient (absolute agreement); MCMJ_L, Modified Counter-Movement Jump Left; MCMJ_R, Modified Counter-Movement Jump Right; MDC, minimal detectable change calculated as SEMx1.96x√2. P<0.05; SEM, SE of the measure calculated as the square root of the residual mean square.
were not. We suggest that this infers the amount of vari-
those who were subsequently injured and those who

group differences being 8.4° and 7.6°, respectively, for
the between

abduction at initial contact and peak during a drop jump
allows for adequate planning (power analyses) of inter-

results found for left side compared with right. Posi-
regarding all rotational movements. Regarding peak
angles, we noticed slightly, but inconsistently, better

important role in the

results obtained. Variations in footwear type and sole
height may have caused variations in ankle joint centre
detection, reducing measurement accuracy. Addition-

better assess if this approach would be viable for their
specific situation.

Some limitations should be considered in the inter-

of the study. Differences in the
definition of reference systems and processing between

UTURE investigations should use standardised footwear
frontal plane may positively influence the extracted data.

LOA (deg)

Table 8

| Test     | Movement   | Lower LOA (deg) | Upper LOA (deg) | Bias (deg) |
|----------|------------|-----------------|-----------------|------------|
| SLS_L    | Hip flexion| −0.9            | 21.6            | 10.3       |
|          | Hip adduction| −7.4          | 11.1            | 1.8        |
|          | Knee flexion| −9.6            | 4.1             | −2.8       |
|          | Knee adduction| −9.5          | 5.0             | −2.2       |
| SLS_R    | Hip flexion| 3.8             | 25.7            | 14.7       |
|          | Hip adduction| −11.6         | 2.9             | −4.4       |
|          | Knee flexion| −10.4           | 5.2             | −2.6       |
|          | Knee adduction| −4.7          | 11.8            | 3.6        |
| SLJ_L    | Hip flexion| −2.5            | 21.4            | 9.5        |
|          | Hip adduction| −8.2          | 7.7             | −0.2       |
|          | Knee flexion| −8.6            | 8.0             | −0.3       |
|          | Knee adduction| −7.1          | 2.2             | −2.5       |
| SLJ_R    | Hip flexion| −0.1            | 27.8            | 13.9       |
|          | Hip adduction| −13.2         | 7.2             | −3.0       |
|          | Knee flexion| −9.1            | 8.1             | −0.5       |
|          | Knee adduction| −0.9          | 10.0            | 4.5        |
| MCMJ_L   | Hip flexion| −3.3            | 17.1            | 6.9        |
|          | Hip adduction| −10.4         | 3.6             | −3.4       |
|          | Knee flexion| −9.2            | 4.0             | −2.6       |
|          | Knee adduction| −8.9          | 4.1             | −2.4       |
| MCMJ_R   | Hip flexion| 1.0             | 20.4            | 10.7       |
|          | Hip adduction| −4.7          | 12.4            | 3.8        |
|          | Knee flexion| −9.2            | 4.4             | −2.4       |
|          | Knee adduction| −3.1          | 10.6            | 3.8        |

LOA, limits of agreement; MCMJ_L, Modified Counter-Movement Jump Left; MCMJ_R, Modified Counter-Movement Jump Right; SLS_L, Single Leg Squat Left; SLS_R, Single Leg Squat Right.

protocol. In comparison to the displayed MDC values
here, we suggest that both the markerless and mark-
er-based approaches can readily detect such changes. Further to this, it was noted that the hip flexion angle
appeared to have a systematic error of approximately
10° when comparing the markerless and marker-based
systems. Post processing (ie, subtracting 10° from all
measures) could simply remove this artefact and result in
more accurate measures. It is uncertain from where this
shift arises; however, the closed nature of the processing
conducted through the markerless software capture
and subsequent processing likely render this a difficult
problem to resolve.

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