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DRISCOLL, Heather, KELLEY, John <http://orcid.org/0000-0001-5000-1763>, KIRK, Bob, KOERGER, Harald and HAAKE, Steve <http://orcid.org/0000-0002-4449-6680>

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Heather Driscoll[a], John Kelley[a], Bob Kirk[b], Harald Koerger[b] and Steve Haake[a]

[a] *Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, UK*

[b] *ait. adidas-innovation-team, adidas-AG, World of Sports, 91074 Herzogenarauch, Germany*

Corresponding author: Dr Heather Driscoll, Centre for Sports Engineering Research, Sheffield Hallam University, Collegiate Crescent, Sheffield, S10 2BP UK
Phone: +44 (0) 114 225 3987 Email: H.F.Driscoll@shu.ac.uk

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[21] Driscoll HF (2013) Understanding shoe-surface interactions. Doctoral Thesis, Sheffield Hallam University

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Abstract

Interaction between studded footwear and performance surfaces plays an important role in sport. Discretising this interaction into quantifiable measurements can help optimise design of outsoles and identify parameters for performance testing *in situ*. Here we describe the development and validity of an image based three-dimensional (3D) measurement system to investigate shoe-surface interactions during locomotion performance *in situ* by eight skilled footballers. By calculating individual stud positions, results revealed that the 3D kinematic data could be distilled to a number of shoe-surface interaction metrics such as orientation, velocity, translation distance and location of the centre of rotation. Findings show how the measurement system and simple analysis methods can be used to provide informative shoe-surface interaction metrics from *in situ* performance capture for the footwear community.

Keywords

Shoe-surface interactions, Studded boot, Stud configuration, Traction testing, Photogrammetry, *In situ* performance analysis

1 Introduction

Studded sports shoes are used primarily for natural turf based sports such as football (all codes), rugby and field hockey. They are perceived by many as a tool [1] forming the fundamental link between an athlete and a surface. How a shoe interacts with a surface has been shown to influence athlete performance [2] and can provide insights in estimating the likelihood of injury. In physics, the term *interaction* refers to the transfer of energy between objects; for shoe-surface interactions we are primarily concerned with a surfaces' ability to resist the motion of a shoe, i.e. the transfer of kinetic energy from a shoe to a surface. Shoe-surface interactions can be divided into two resistive components: vertical and horizontal. Vertical resistance to motion of a shoe by a surface evidences the ability of a studded outsole to penetrate the surface. Stud penetration is considered to be influenced by surface hardness and stud shape [3]. Horizontal resistance of motion between the outsole of a shoe and a surface is known as traction [4], the level of which can be altered by modifying the outsole stud configuration or stud profile [5] and is also dependent upon surface condition [6].

To quantify shoe-surface interactions mechanical tests are often used to manipulate outsoles across surfaces; ranging from penetrometers to motor-driven traction test devices [5-9]. Traditionally two types of mechanical tests are used to assess traction: (1) measuring the translational traction by pulling a studded shoe or plate across a surface and recording the resistance to motion, or (2) determining the rotational traction by measuring the torque required to rotate a shoe or plate when in contact with a surface. Mechanically quantifying a surface in this way enables researchers to develop their understanding of the 'micro' level interaction between the studs and a surface; for example how soil or rubber particles displace when a stud ploughs through a surface. A problem arises when mechanical test results are erroneously extrapolated to infer how a human will perform with a shoe and/or on a surface being tested. This is because the resulting shoe-surface interaction is not only dependent on the mechanically measured properties of the shoe or surface, but also on the dynamic movement patterns of individual athletes ('macro' level interaction). These movement patterns are often unique to each athlete and can vary with each performance trial [10]. Individual constraints and neuromusculoskeletal strategies (for example, due to prior experiences or perception on the how the outsole will perform) can all influence how an athlete organises movements, whether consciously or not [11]. An outsole design based purely on mechanical test measurements can often have conflicting responses when actively used by an athlete during performance. For example, bladed stud configurations have been shown to have comparatively lower rotational traction measured mechanically [12], but yet, are often cited (especially in the UK media) as the contributing factor to lower limb injuries caused by excessive stud fixation [13]; both may be true but offer contradictory outcomes. For these reasons we sought to advance understanding by analysing shoe-surface interactions when shoes are worn by participants under *in situ* dynamic performance constraints to complement data from analyses when a shoe-surface combination is tested mechanically.

If mechanical tests are to be used to infer human performance (mechanical traction testing has the advantage of being more repeatable and less subjective [14]), the tests need to be representative of task performance. Conducting both mechanical and human performance testing is an optimal strategy (as recommended by Frederick [15] and Nigg [16]), but is not always possible, especially when time constraints dictate the level of testing. This is important since replicating a complete movement (of, for example, an observed injury scenario) with a mechanical device may not provide useful insights into shoe design due to significant levels of individual movement pattern variability observed during actual human performance. Here we demonstrate how a shoe's interaction with a playing surface can be discretised into a number of quantifiable measures during *in situ* performance analysis. In essence, we observe shoe-surface interactions during performance of a complex biomechanical movement and distil it down into an achievable engineering solution. Measures from such *in situ* performance analyses should better inform parameters for mechanical testing allowing them to replicate task performances or influence design changes for footwear.

Kirk *et al*. [17] first introduced the notion that kinematic information could be used to inform outsole design. A single high-speed video camera was used to calculate the orientation and velocity of a shoe during realistic soccer movements on a natural turf surface. However, the study was limited to two-dimensions (2D) and no information was available when the studs were obscured from view (i.e. during surface penetration). To further develop this methodology to include three-dimensional (3D) analysis, multiple cameras are generally required, termed stereo-photogrammetry. Commercial motion capture systems are commonly used within the biomechanics community to collect such data, but are often restricted to a laboratory environment, are expensive and may involve intrusive marker set-ups, all of which may modify participant performance behaviours [18]. In this study we describe the development of a relatively inexpensive motion capture system intended to minimise potential interference with participant behaviour. An image based measurement system was also designed to calculate the position of individual outsole studs during interactions with a performance surface.

2 Methodology

The 3D measurement system first used stereo-photogrammetry to capture the motion of participants' shoes while they perform athletic movements in any test environment (for example, in a laboratory but especially outside *in situ* on a natural playing field). To progress the previous work of Kirk *et al*. [17], rigid body calculations were used to calculate stud locations enabling their position to be estimated even when obscured from view (i.e. during surface contact). Shoe-surface interaction metrics were next identified from the information on individual stud location. Although the approach of using stereo-photogrammetry to capture biomechanical motion data is not novel, an important advance in this study concerns the integration of such a system for calculation of stud location and corresponding shoe-surface interaction analysis whilst participants performed movements. The development of the data collection system and post processing techniques are discussed below. An adidas Copa Mundial soccer shoe was used in the following methodology sections, although the same procedure can be applied to use of any studded outsole.

2.1 Motion capture

Stereo-photogrammetry

Two high-speed video cameras (Phantom v4.3) were positioned approximately 5 m away from the test zone at an angle of 70° to each other. The following camera settings were used: 1000 fps, exposure 70 µs, 0.6 s event duration and resolution of 512 x 382 pixels. The cameras were calibrated using the planar (checkerboard) technique [19, 20]. A maximum calibration re-projection error of ± 0.4 pixels (approximately ± 0.8 mm) was calculated for a test volume of approximately 1.5 x 1.5 x 1.0 m^3. A global coordinate system was defined at the centre of the test volume such that the y axis was in the direction of motion, the x axis was medial to the direction of motion and the z axis was vertical.

Marker tracking algorithm

Four, white high contrast markers (retro-reflective paint, 8 mm diameter) were positioned on the left shoe and were used to define two rigid bodies representing the rear-foot and forefoot sections of a shoe (Fig. 1a). A semi-automated tracking method was developed using MATLAB® image processing algorithms to allow fast and efficient acquisition of marker coordinates. The tracking tool required the user to first select the marker and input the number of frames over which to track. Self-windowing and binary conversions were then used to automatically identify the selected marker over the remaining frames, returning the 2D image coordinates of the marker. If no marker was found, a predicted position was calculated from the marker positions at the previous two time-steps, until the marker could be detected again. Stereo-triangulation was used to convert the 2D image coordinates from the left and right camera views into 3D global coordinates. The 3D coordinates were smoothed using a five-point moving average filter.

2.2 Calculation of stud position

The assumption was made that the shoe acted as two rigid bodies rotating about a hinge axis running approximately medial-laterally and positioned near the metatarsal-phalangeal joint. The rear-foot rigid body was defined by three markers positioned on the lateral side of the shoe near the heel (P1), ankle (P2) and proximal to the metatarsal-phalangeal joint (P3). The forefoot rigid body was defined by a fourth marker at the toe (P4) and two pseudo-markers (P5 and P6) positioned on the lateral and medial sides of the hinge axis (Fig. 1a). Fixed position markers were not used for the forefoot section as excessive deformation of a shoe upper rendered it difficult to position a marker without invalidating the rigid body assumption. The shoe consisted of 12 studs, four on the heel and eight on the forefoot; the heel studs and the rear most stud on the lateral side of the forefoot were associated with the rear-foot rigid body, and the remaining studs with the forefoot rigid body (Fig. 1b). The rear-foot and forefoot stud allocation was based on observation of the shoe flexing about the forefoot during a heel-strike to push-off walking movement.

Fig. 1a and 1b about here

The following protocol was used to calculate the stud positions during movement trials:

(1) The stud and marker coordinates of the shoe were measured in a static reference position;
(2) The hinge axis position and direction was calculated from a heel-plant to toe-off walking trial;
(3) Two pseudo-markers on the medial and lateral sides of the shoe on the hinge axis were calculated;
(4) The pseudo-marker locations were defined relative to the static reference position;
(5) Transformation matrices from side marker to stud position for the rear-foot and forefoot using the reference position were calculated;
(6) The side markers were tracked during a movement trial using the semi-automated tracking algorithm;
(7) Inverse transformations were applied to obtain the stud positions.

Reference position of studs and markers

A shoe was placed on a flat glass surface and positioned such that the rear most heel studs (S1, lateral side and S2, medial side) and rear most forefoot stud (S3, lateral side) formed a local coordinate system (where S1 = origin, S1 to S2 = x axis and S1 to S3 = y axis). Shoe markers were measured relative to the local coordinate system using a right-angled arrangement of metal rulers (accuracy ± 0.5 mm) perpendicular and parallel to the axis system. The glass surface and shoe were then rotated such that the studs were visible. The centre of the studs (x, y position) were then measured relative to the local coordinate system (accuracy ± 0.5 mm), with the vertical (z) coordinate measured using digital callipers (distance from the centre of the stud to the glass plate surface, accuracy ± 0.1 mm). The position of each stud and marker in the local coordinate system were recorded and saved as the reference position.

Identifying a hinge axis

To identify the hinge axis between the rear-foot and forefoot rigid bodies a participant was asked to walk through the stereo-calibrated volume performing a heel-plant to forefoot push-off. One trial of this movement was required for each participant from the data collection study cohort. This allowed the hinge axis position to be customised to the individual, increasing the validity of the two rigid-bodies assumption. The three rear-foot markers were tracked during the movement and data were obtained on the position and direction of the hinge axis (Fig. 2) using the following methodology:

(1) A time period (t_1 to t_2) in which the forefoot studs of the shoe were observed to be fully in contact with the surface and rear-foot studs were out of contact was identified from the video footage.

(2) The position vectors of the rear-foot markers were identified at the start and end of the selected time period (P1, P2, P3 at t_1 and P1', P2', P3' at t_2).

(3) Three planes were calculated: one plane defined as equidistant from P1 and P1', another equidistant from P2 and P2' and the final plane equidistant from P3 and P3'.

(4) Any pair of these three planes could be used; however, the two planes with the greatest angle between were selected to reduce relative effect of errors.

(5) The line of intersection between the two selected planes was calculated to give the rotation or hinge axis.

Fig. 2 about here

Pseudo-marker location

The above methodology defined the location of the hinge axis in the global coordinate system during the selected walking trial. The next stage was to use the hinge axis to define two pseudo-markers that could be used to complete the rigid body of the forefoot section. First, a plane containing the three rear-foot markers (P1, P2 and P3) at the first time step was calculated. The point of intersection of this plane and the line through the rotation axis was then determined; this formed the first pseudo-marker (P5) (Fig. 2). A second point 100 mm along the hinge axis from P5 was calculated to determine the second pseudo-marker (P6). A distance of 100 mm was selected for the second pseudo-marker; this distance is arbitrary, but in this instance it approximately related to the width of the forefoot. In order for the pseudo-markers to be used in other trials, their position relative to the marker P4 needed to be defined. This required calculating a transformation matrix to determine the pseudo-marker position in the reference frame. The process of obtaining the transformation matrix formed an integral part of the methodology and is used a number of times to obtain the final stud position.

Transformation matrix

The transformation matrix, [M] was calculated in MATLAB® and defined as follows:

$$[M] = [R][T] \tag{1}$$

where [T] is the translation matrix to set P1 to the origin and [R] is the rotation matrix for an XZY rotation sequence in which P3 is firstly rotated onto the x-y plane, then onto the y-z plane and finally P2 is rotated onto the x-y plane.

Equation 1 was used to calculate the transformed position of the rear-foot studs when using P1, P2 and P3. The transformed position of the pseudo-markers and P4 were then calculated relative to P1, P2 and P3. Finally, the forefoot studs were transformed relative to P5, P6 and P4 (replacing P1, P2, P3 respectively in the above calculation).

Calculating final stud position

To obtain the final stud positions during each movement trial firstly required the side markers to be tracked and converted to 3D coordinates. The rear-foot marker coordinates were then transformed using Equation 1 and the inverse transformation matrix, $[M]^{-1}$ used to obtain the rear-foot stud positions and the pseudo-marker positions. The pseudo-markers and forefoot marker were then transformed as above and the inverse transformation matrix used to determine the forefoot stud locations. Knowledge of stud location during each movement trial yielded further information such as time of surface contact of individual studs.

2.3 Calculation of shoe-surface interaction metrics

Orientation

The orientation of the shoe was defined using the local coordinate system on the rear-foot of the shoe. The three Euler angles (pitch, yaw and roll) were calculated using the direction cosine matrix formed by transforming the local coordinate system onto the global coordinate system. The MATLAB® script used to calculate the transformation matrix was again used, substituting the side markers (P1, P2 and P3) for the three stud positions (S1, S2 and S3 respectively). The pitch angle corresponded to the first rotation about the x-axis, the yaw angle the second rotation about the z-axis and finally, the roll angle was the last rotation about the y-axis. The pitch, yaw and roll angles were non-commutative and are reported in degrees. Positive pitch angles corresponded to the shoe being in a toe-up position, positive yaw to a toe-in position and positive roll corresponded to an outward rotation of the shoe.

Velocity and acceleration

The velocity of each stud was derived from stud coordinates using the central differencing method over five time steps and smoothed using a five-point moving average filter [21]. Acceleration was calculated from the un-filtered velocity data using a three-point central differencing method.

Translation

Translation of the shoe (or slip) was defined as being a period of significant stud motion in the horizontal direction with little or no motion in the vertical direction, and/or with little or no change in pitch angle during stud-surface contact. These constraints eliminated the likelihood that the change in horizontal motion was due to the shoe lifting off the surface. The stud coordinates during surface contact were also viewed on a 2D horizontal plane (turf surface) to note the dominant motion direction during the movement; the plots produced using this approach were known as the stud translation vectors.

Rotation

The 2D centre of rotation of the shoe during contact with the surface was calculated using the Reuleaux method. The Reuleaux method states that the displacement of any rigid body in 2D can be represented by a rotation of angle, θ about a pole of displacement (or centre of rotation, I), if the location of two points on the rigid body are known (stud positions) (Fig. 3). Full details of the Reuleaux method can be found in the paper by Eberharter and Ravani [22].

3 Validation and error analysis

3.1 Stereo-photogrammetry and marker tracking

Reliability

The reliability of the semi-automated tracking algorithm was assessed by tracking two markers over 26 frames and repeating five times for both the left and right camera images. The standard deviation of the distance between image coordinates of the markers from the five repeats was averaged to give the mean standard deviation in pixels. The mean standard deviation in marker coordinates tracked using the semi-automated algorithm was ± 0.25 pixels. Propagating this to 3D global coordinates after stereo-triangulation led to a mean standard deviation of ± 0.5 mm.

Repeatability

To assess the error arising from changes in test conditions, camera position and participant repeatability, a reliability study was carried out over two separate test days. The same participant was involved in both tests and was asked to perform a sprint movement five times. The same cameras were used for testing but the position varied between the two test days. The velocity of marker P3 in the vertical direction at touch-down was used for comparison. The mean velocity from the five trials on each test day was calculated. The absolute difference between the two mean velocity values was 0.18 ms^{-1}. A *t*-test indicated that there was no significant difference between the impact velocities at the p = .10 level. It is likely that differences observed were due to participant familiarity rather than the measurement system, indicating that in future research a habituation period prior to testing may be required.

Validation

The 3D marker coordinates resulting from the stereo-photogrammetry method and tracking algorithm were validated by comparison with a laboratory based Motion Analysis Capture (MAC) system. The MAC system is reported to have an accuracy of 0.1 mm [23] and was considered the gold standard for this analysis. A reflective marker was rotated in a circular horizontal trajectory at a constant rotational velocity of 60.0 rpm and fixed radius of 400 mm using a motor driven device. A second static marker was placed on the rotation centre of the device. Both markers were tracked using eight infrared cameras for the MAC system and two high-speed cameras for the stereo-photogrammetry method. The coordinates obtained from the MAC system were compared to the results from the stereo-photogrammetry system after stereo-triangulation. The radius of rotation was calculated from the resultant distance between the static marker and the rotating marker. A mean over 147 time-steps (0.588 s) was calculated and compared to the true value of 400 mm. The mean angular velocity was further calculated from the angular displacement of the rotating marker relative to the static marker and compared to the true value, 60.0 rpm (6.28 rad/s). Both tracking systems were within 99% of the true values for both the radius and angular velocity (Table 1), suggesting that the stereo-photogrammetry system was acceptable for use in motion capture scenarios.

Table 1 about here

3.2 Stud position and contact timing

To verify the time of initial stud-surface contact (touch-down), the stereo-photogrammetry system was synchronised with a force plate (Kistler 9281) sampling at 1000 Hz. A falling edge trigger with a 5 N threshold was used to define the time of touch-down from the force data. The time of peak vertical acceleration of marker P3 was used to define touch-down from the kinematic stereo-photogrammetry data. The agreement between the two events suggested that it was appropriate to use the peak acceleration of marker P3 to define touch-down when force data were unavailable (for example, in ecological test environments). A similar approach was used by Hreljac and Marshall [24] in determining event timing with kinematic data during walking.

Individual stud contact timings and positions were evaluated by comparison to the results obtained from performing the test on a pressure-mat (RSscan footscan®, 2D plate 0.5 m, 200 Hz). A participant was asked to walk across the pressure-mat performing a heel-plant to toe push-off movement. The pressure results from the mat enabled the time of contact to be determined. The initial contact time of each stud was obtained and compared to the predicted contact time from the stereo-photogrammetry system (Fig. 4). As it was not possible to synchronise the two measurement systems, the first stud to contact the surface (S1) was set to time 0 s.

Fig. 4 about here

The mean absolute difference between stud contact detected by the pressure mat and that estimated from stereo-photogrammetry was 0.033 ± 0.031 s. The closest match was seen for the heel studs (S1, S2, S4 and S5), with a mean absolute difference of 0.016 s, the stereo-photogrammetry system indicated a slight delay in detecting contact for the heel studs. The mid-foot studs (S3, S6, S7 and S8) were also in good agreement, with a mean absolute difference of 0.033 s. The toe studs (S9, S10, S11 and S12) showed the greatest difference with a mean absolute difference of 0.051 s, in general the stereo-photogrammetry system predicted contact earlier for the toe studs than that seen by the pressure mat. The mid-foot and toe studs were calculated from the forefoot rigid body using the pseudo-markers on the hinge-axis. It was anticipated that this additional calculation would increase the error in stud location prediction, but comparison with the pressure mat data revealed that the differences seen in contact time between studs were not significant (Spearman's rho $\rho = .96$).

4 Practical assessment

4.1 Pilot data collection study

To assess the feasibility of the system for collecting data and interpreting the results, a pilot data collection study was carried out by observing movement performance of eight participants (following informed consent and approval from the institution's ethics committee) from Doncaster Rovers Youth Development Team (17.1 ± 0.5 years). Participants were asked to complete five repetitions of an acceleration movement (6 m jog followed by 6 m sprint) selected as it required high levels of traction and was similar to that used by Kirk *et al.* [17]. Data collection took place on a natural grass surface (FIFA standard ball rebound of 40%). The stereo-photogrammetry technique and tracking algorithm were used to track the shoe markers for each trial. A time period in which the forefoot of the shoe remained in contact with the ground and the rear-foot section rotated off the surface was used to determine the hinge-axis and pseudo-marker location for each participant. Data from a representative trial will be presented here to demonstrate the role of inexpensive and simple methodology and analysis technique for sampling shoe-surface interaction information from *in situ* movement performance. The use of single trial analysis has been previously justified in the literature [10] and is relevant due to the inherent variability present in human kinematic behaviour in line with the premise that "averaging" performance data across participants can often create a set of results that does not resemble any of the individual trials.

4.2 Orientation and velocity

During the exemplar trial the shoe was observed to impact the surface in a toe-down position with the forefoot studs coming into contact first at a pitch angle of -16° and impact velocity in the y-z plane of 1.5 ms^{-1}. The yaw angle was -25°, such that the forefoot of the shoe rotated outwards while the roll angle was small enough to be negligible (Fig. 5).

Fig. 5 about here

4.3 Stud contact timing

Five of the forefoot studs were observed to come into contact with the surface almost simultaneously upon foot-strike. By approximately 35% stance time all the forefoot studs were in contact, throughout the movement, the heel studs did not come into contact with the surface. During the push-off phase, stud S12 was the last stud to remain in contact with the surface, Fig. 6 illustrates the order in which the studs left the surface.

Fig. 6 about here

4.4 Centre of rotation

During the midstance phase (20 - 60% stance time) of the exemplar trial, the shoe was observed to rotate outwardly with greater displacement of the lateral forefoot studs compared to the medial side. The calculated centre of rotation was position just outside the medial edge of the forefoot as shown in Fig. 7.

Fig. 7 about here

5 Limitations

The following limitations of the measurement system have been acknowledged:

(1) The shoe was assumed to be comprised of two rigid bodies pivoting about a hinge axis. Calculation of the hinge axis from movement trial data allowed two pseudo-markers to be defined to form the forefoot rigid body. Deformation to either the rear-foot or forefoot rigid bodies introduces inaccuracies in the matrix transformation to calculated stud position. For future testing, further analysis into the optimum marker set and number of rigid bodies required to reduce the measurement error is recommended.

(2) Circular tracking markers were used which have the potential to introduce eccentricity errors; they were however less obtrusive and less prone to movement error than spherical markers. The marker size was approximately 1-2% of the total image size and as such it was expected that the error from eccentricity would be negligible.

(3) The calculation of the 2D centre of rotation assumed no movement occurred in the vertical axis. A 3D approach such as the helical screw axis could be used for situations where substantial motion in more than two planes occurs.

6 Conclusion

A method for obtaining 3D kinematic information of a studded shoe prior, during and after contact with a turf surface has been established for *in situ* testing. The technique is relatively inexpensive compared to existing methods and requires only two cameras with a simple calibration procedure. The markers on the shoe are passive and non-obtrusive and are not likely to influence participant performance. This relatively inexpensive and simple to use system has an accuracy level comparable to that of a more expensive, commercially available multi-camera system (Table 1) with the considerable advantage that it can be used to analyse stud-surface interactions during movement performance *in situ*. Image processing techniques allowed the footage to be analysed efficiently and accurately (± 0.5 mm) with minimal user intervention. Rigid body calculations were used to determine the location of the studs from the 3D position of the tracking markers. This allowed the stud position to be estimated when they are occluded (for example, during penetration with the surface). Stud positions were verified by comparison with performance on a pressure mat (Spearman's rho $\rho = 0.96$). The 3D kinematic data were then distilled down to a number of quantifiable measures such as shoe orientation, velocity or the location of the centre of rotation. More extensive data collection needs to be undertaken in future research to investigate the changes in shoe movement parameters during a variety of different motions, outsole designs and surfaces.

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Tables

Table 1 Radius and angular velocity of marker trajectory (mean ± S.D.)

	MAC	**Stereo-photogrammetry**	**True value**
Radius (mm)	398.5 ± 0.3	399.4 ± 0.8	400.0
Angular velocity (rad/s)	6.27 ± 0.45	6.26 ± 0.56	6.28

Figure captions

Fig. 1a Marker positions on the left shoe forming two rigid bodies (rear-foot and forefoot) - the dashed line indicates the pseudo-marker P6 is on the medial side of the shoe; **1b** Stud location numbering convention (studs S1, S2 and S3 form the local coordinate system) - black studs lie on the rear-foot, grey studs on the forefoot.

Fig. 2 The hinge axis was formed from the intersection of the two planes equidistant from P3-P3' and P1-P1'. The pseudo-marker is formed from the intersection of the plane through the points P1, P2 and P3 and the hinge axis. Please see Fig. 1 for the location of markers P1, P2 and P3 on the shoe.

Fig. 3a Reuleaux method used to calculate the centre of rotation from two stud coordinates (Modified from [23]) **3b** Example of shoe rotating from position P to P'

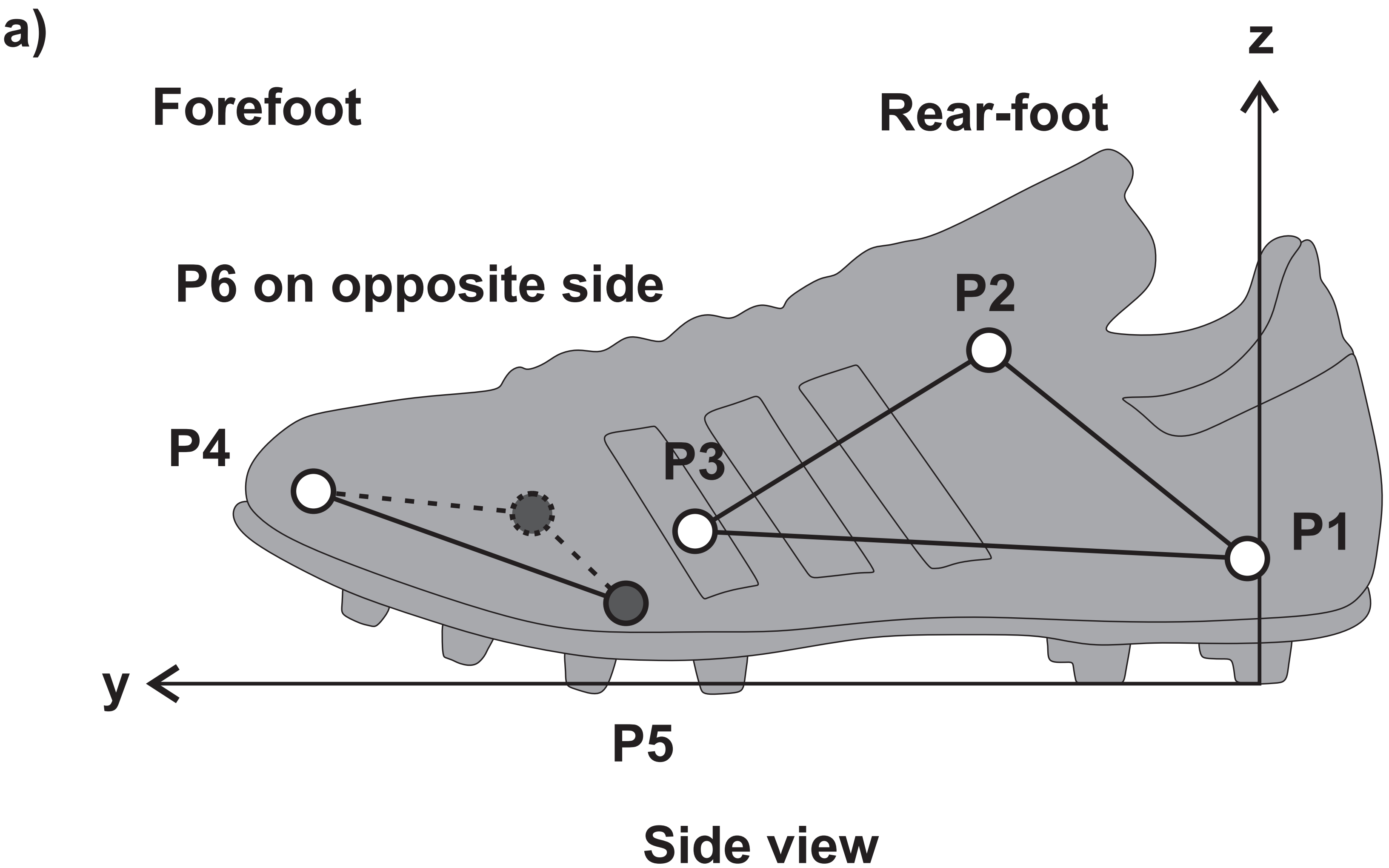
Fig. 4 Time of contact of each stud found from the pressure mat and calculated using the stereo-photogrammetry method

Fig. 5 Orientation and velocity vectors for the forefoot studs at touch-down for the sprint movement

Fig. 6 Time of stud release from the surface for the sprint movement (at push-off)

Fig. 7 Stud position and calculated centre of rotation (shaded circle represents ± 1 S.D., arrow indicates rotation direction)

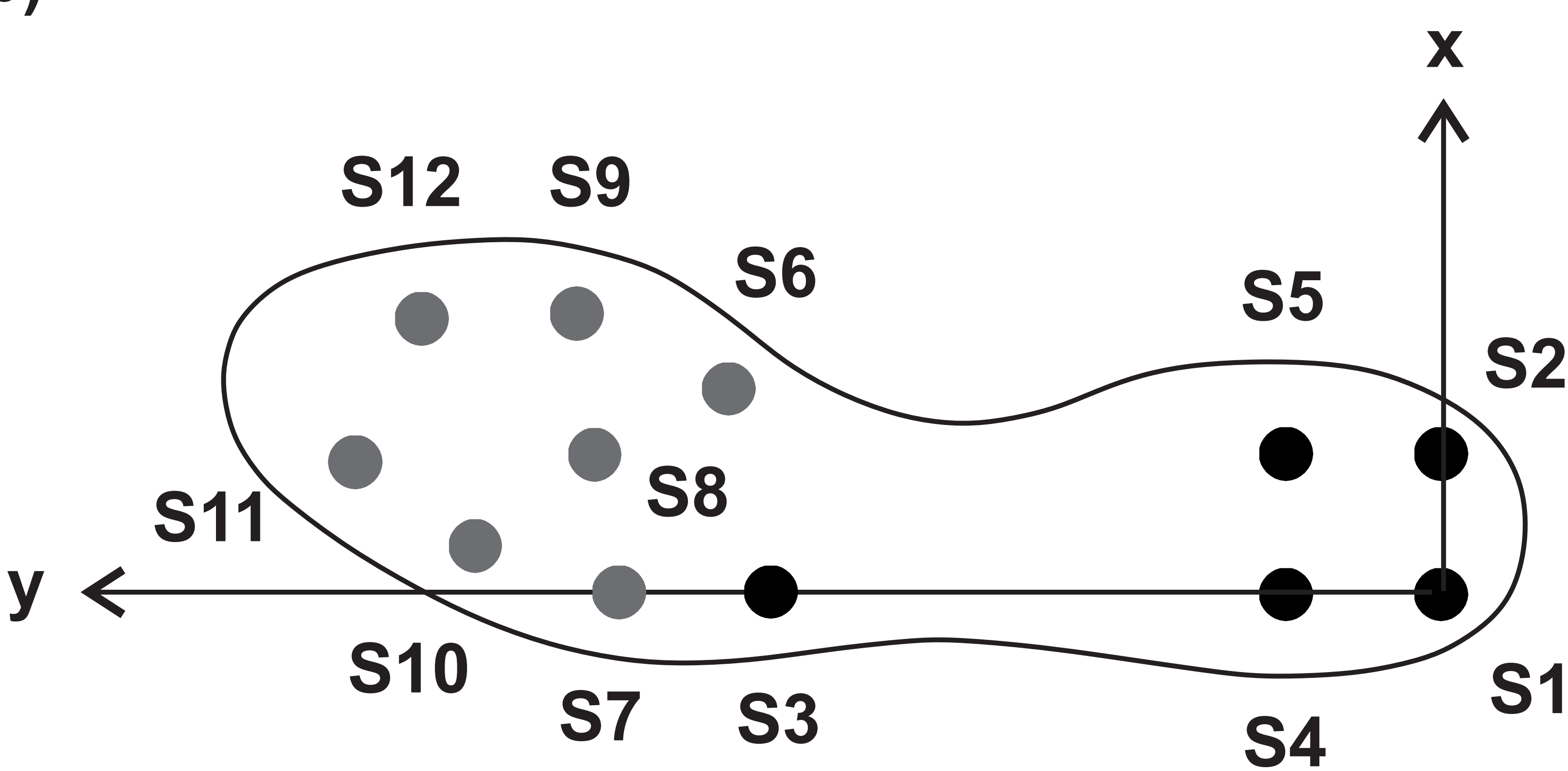
Fig 1a



a)
z
Forefoot
Rear-foot
P6 on opposite side
P2
P4
P3
P1
y
P5
Side view

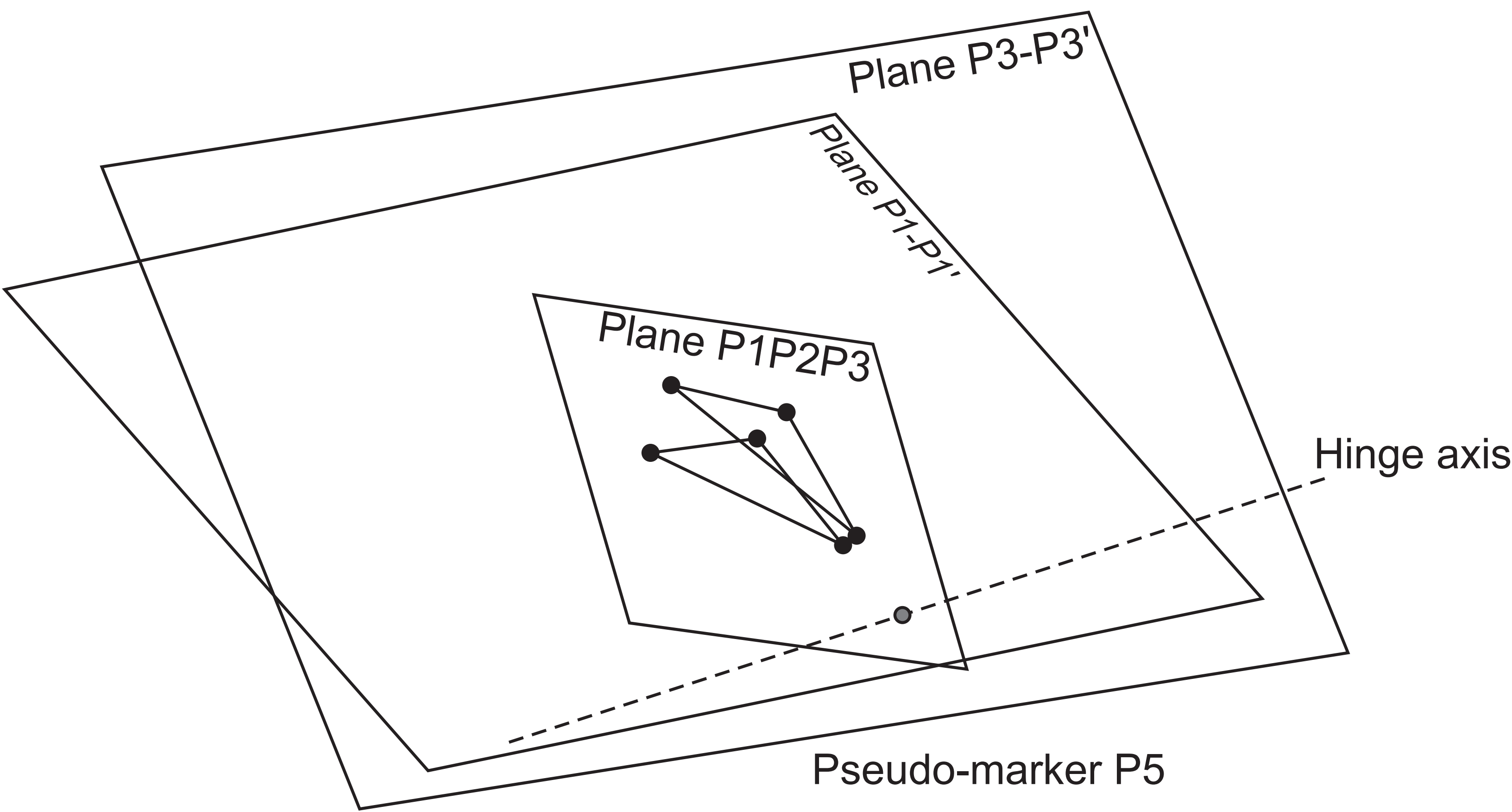
Fig 1b

b)



Plan view

Fig. 2



Plane P3-P3'
Plane P1-P1'
Plane P1P2P3
Hinge axis
Pseudo-marker P5

Fig 3a

a)

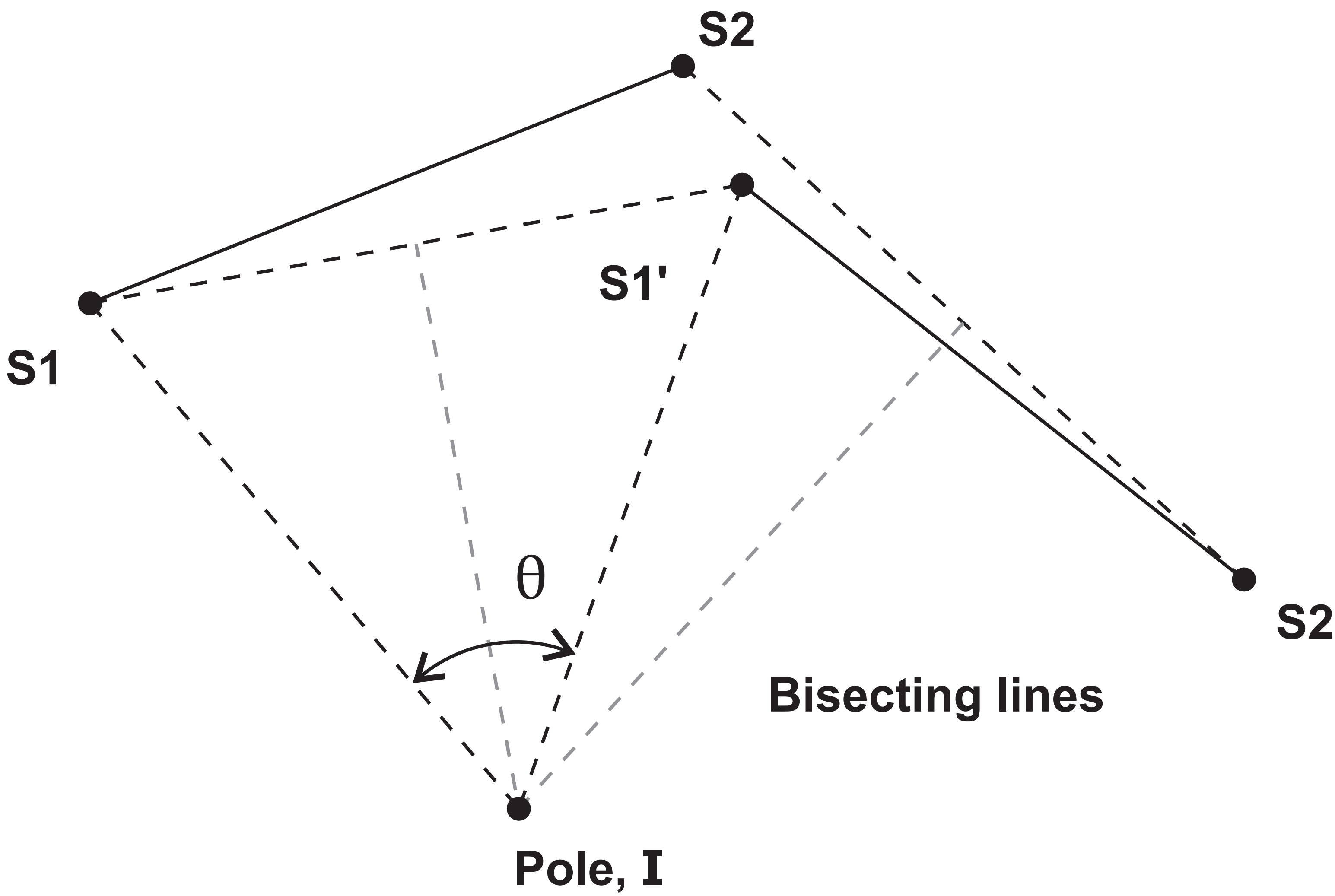


Fig 3b

b)

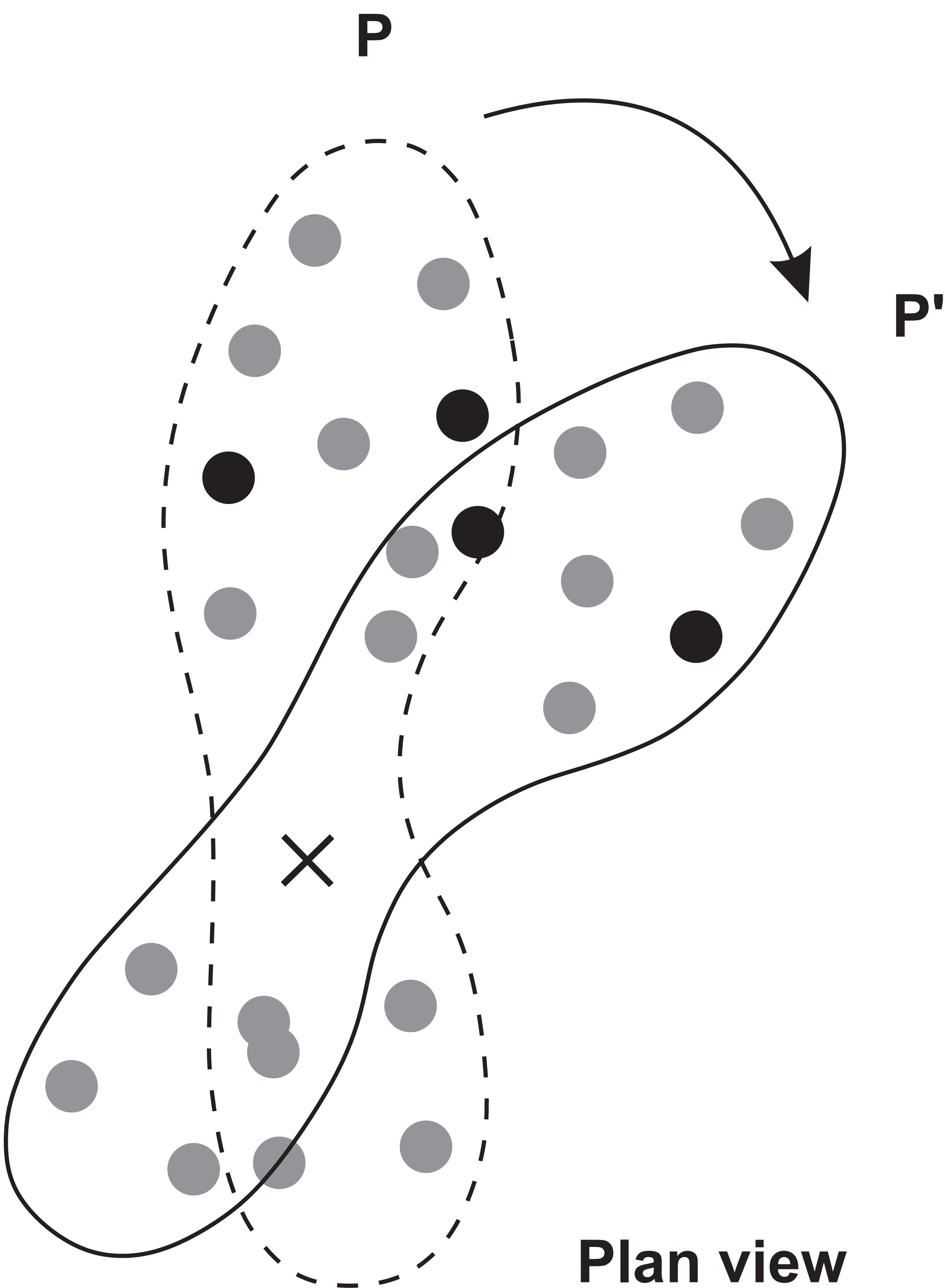
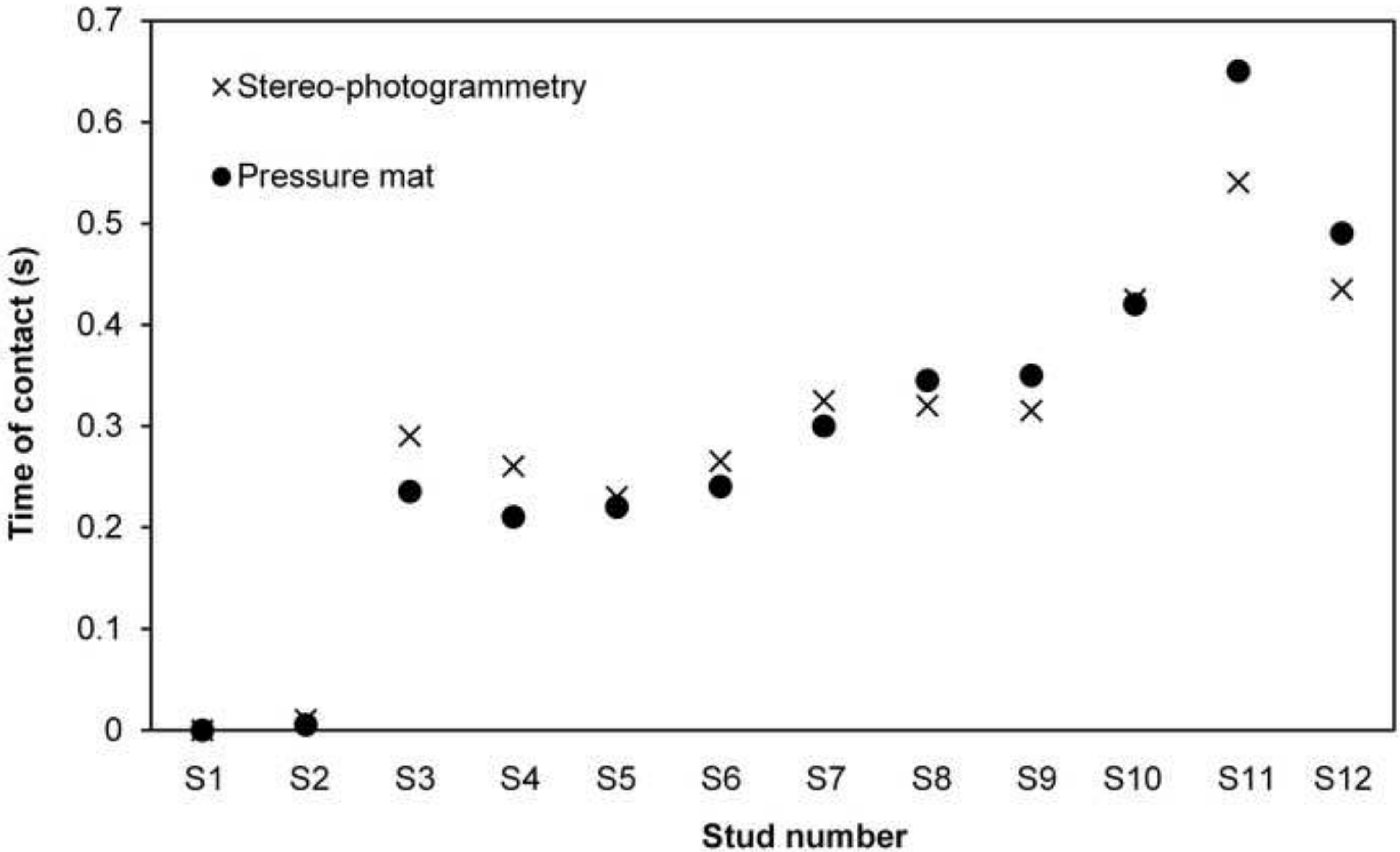
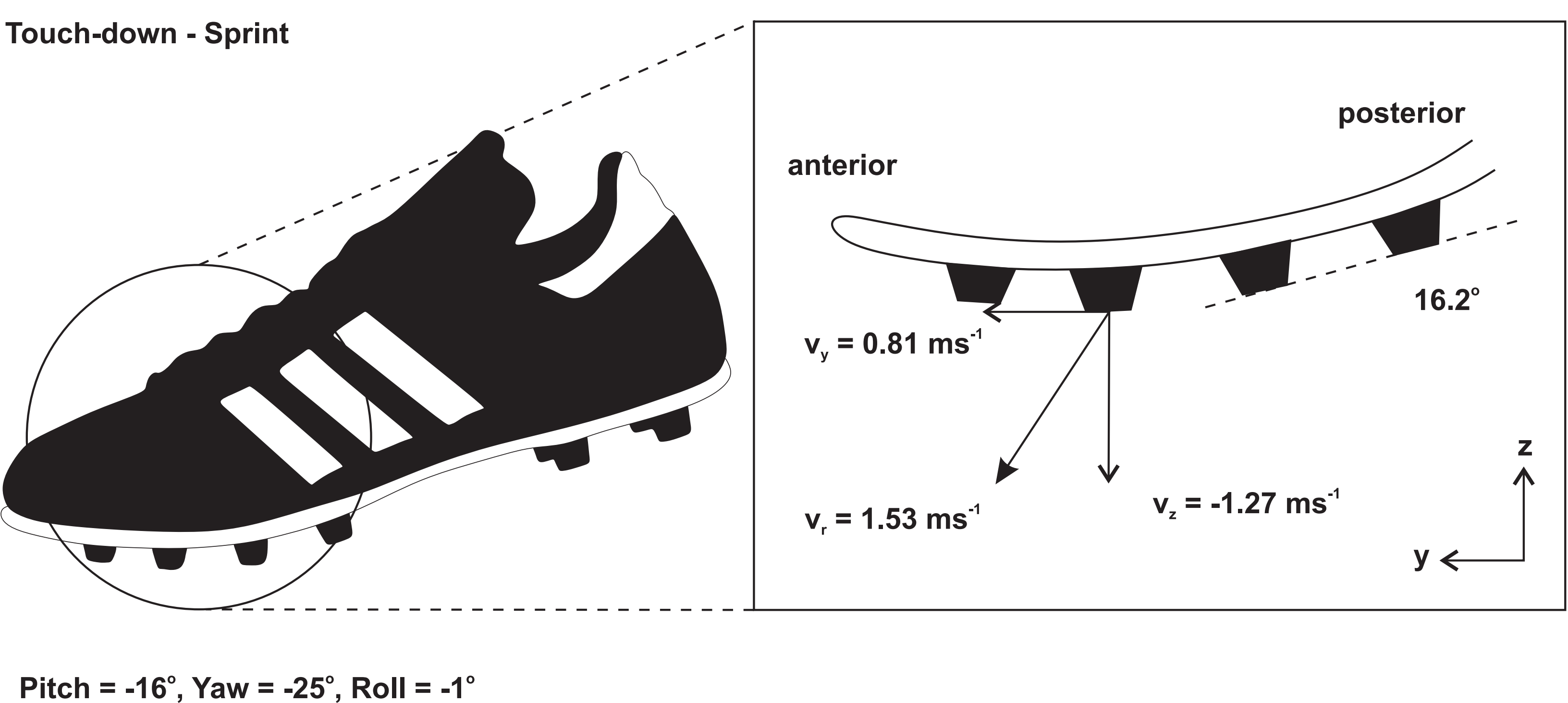


Fig. 4



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time of contact (s)
×Stereo-photogrammetry
●Pressure mat
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
Stud number

Fig 5



Touch-down - Sprint
posterior
anterior
16.2°
v_y = 0.81 ms^{-1}
v_r = 1.53 ms^{-1}
v_z = -1.27 ms^{-1}
z
y
Pitch = -16°, Yaw = -25°, Roll = -1°

Fig 6

Sprint - push-off

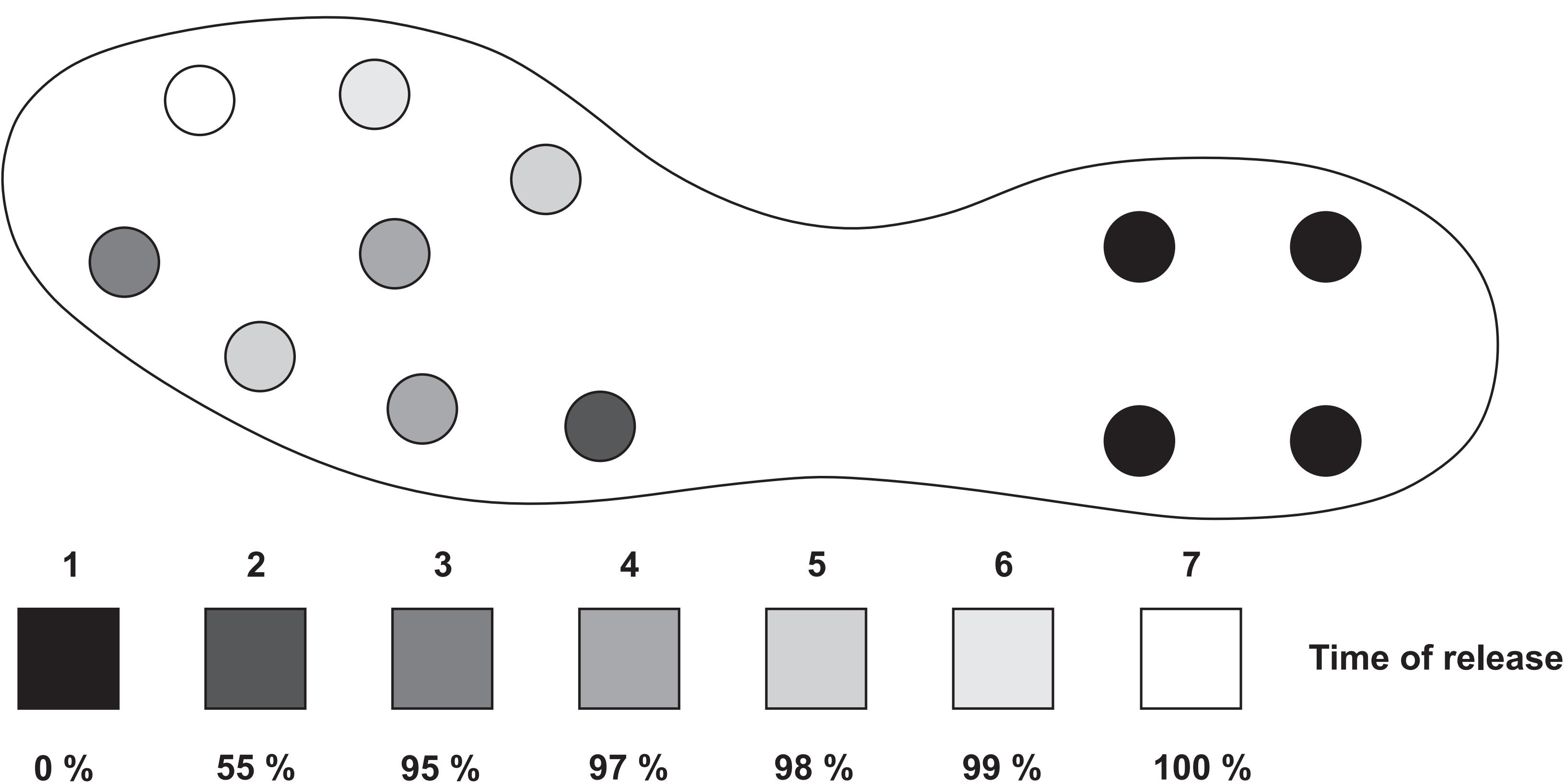
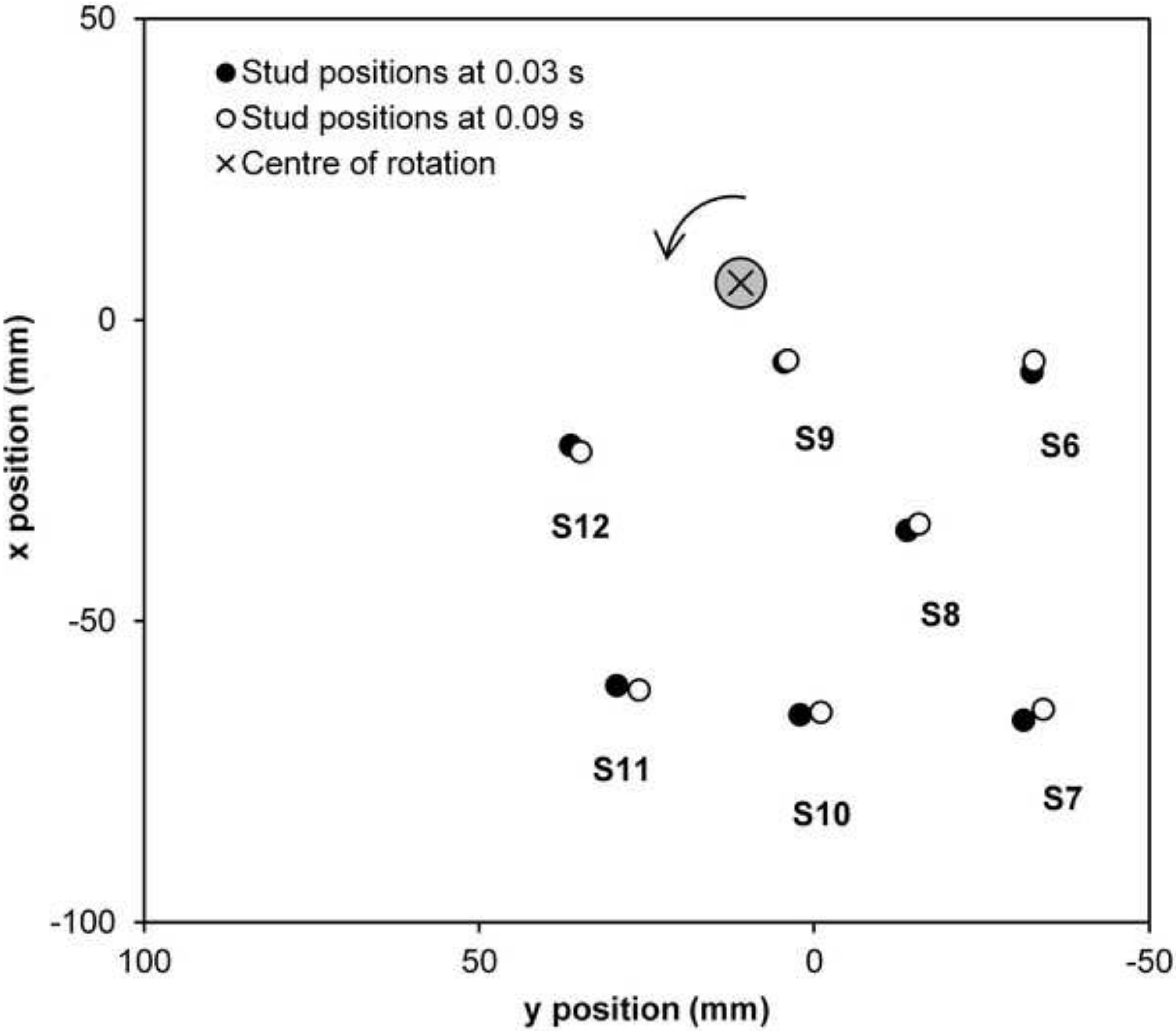


Fig. 7



Stud positions at 0.03 s
Stud positions at 0.09 s
Centre of rotation
S9
S6
S12
S8
S11
S10
S7
x position (mm)
y position (mm)
50
0
-50
-100
100
50
0
-50