The Effect of Coordinate System Variation on *In Vivo* Patellofemoral Kinematic Measures

Angela E. Kedgley, PhD^{a,1}
Emily J. McWalter, PhD^{b,2}
David R Wilson, DPhil^{a,c}

^aDepartment of Orthopaedics
University of British Columbia
3114 - 910 West 10th Avenue
Vancouver, BC V5Z 1M9 Canada

^bDepartment of Mechanical Engineering
University of British Columbia
2054-6250 Applied Science Lane,
Vancouver, BC V6T 1Z4 Canada

^cCentre for Hip Health and Mobility
Vancouver Coastal Health Research Institute
7/F, 2635 Laurel Street
Robert H.N. Ho Research Centre
Vancouver, BC V5Z 1M9 Canada

¹*Present address:* Department of Bioengineering
Imperial College London
South Kensington Campus
London, SW7 2AZ United Kingdom

²*Present address:* Department of Radiology
The Lucas Center for MR Spectroscopy and Imaging
P064-1201 Welch Road
Stanford, CA 94305-5488 United States of America

Correspondence:
Angela E. Kedgley
Department of Bioengineering
Imperial College London
South Kensington Campus
London, SW7 2AZ
United Kingdom

Phone: 011 44 (+0) 207 594 0747
Email: akedgley@imperial.ac.uk

Abstract

Background: The use of different coordinate system definitions for the patella leads to difficulties in comparing kinematic results between studies. The purpose of this work was to establish the effect of using a range of coordinate system definitions to quantify patellar kinematics. Additionally, intra- and inter-investigator repeatabilities of the digitization of anatomic landmarks on the patella were determined.

Methods: Four different patellar coordinate system definitions were applied using digitisations in two and three dimensions and a single femoral coordinate system was used for comparison. Intra-investigator variability was established by having one investigator digitize the patellar landmarks of three subjects on five separate occasions. Inter-investigator variability was quantified by having five participants digitize the same landmarks on the same three subjects. Patellofemoral kinematics were quantified for ten subjects, at six angles of tibiofemoral flexion, using MRI.

Results: As a result of changes in the patellar coordinate system, differences of up to 11.5° in flexion, 5.0° in spin, and 27.3° in tilt were observed in the resultant rotations for the same motion, illustrating the importance of standardizing the coordinate system definition.

Conclusions: To minimize errors due to variability while still maintaining physiologically sensible kinematic angles, a coordinate system based upon an intermediate flexion axis between the most medial and lateral points on the patella, and a

superiorly-directed long axis located between the most proximal and distal points on the patella, with an origin at the centre of the most proximal, distal, medial, and lateral points on the patella is recommended.

Keywords: coordinate system; patella; landmarks; patellofemoral kinematics

1. Introduction

Patellar kinematics have been measured in a wide range of studies of normal, pathological and treated knees. An essential step in describing kinematics is defining a coordinate system at the joint, but there is currently no standard definition of a coordinate system for the patella. This makes comparing results across the literature difficult, if not impossible [1]. The most widely used method of assigning coordinate systems is to select anatomical landmarks that allow the creation of an origin point, a flexion axis, and a long axis. A third axis is determined from the cross product of the long and flexion axes, and an orthogonal flexion axis is then found by taking the cross product of this third axis with the long axis. An orthogonal coordinate system is consequently formed by the second flexion axis, the long axis and the third axis. Many combinations of landmarks have been used to assign coordinate systems to the femur and patella (Table 1), and these are likely responsible, in part, for the variability in patellofemoral kinematics that is seen in the literature.

Alternatives to anatomical coordinate system definitions include fitting a bounding box [22,23] and the recently proposed method of an automated algorithm that makes use of the posterior ridge of the patella [20]. Although these two methods will result in repeatable coordinate frame definitions, their automated nature means that they may not always align with patellar anatomy. In particular, the use of a bounding box is affected by the orientation of the knee in the scanner. Obviously, other confounding factors include natural and pathological anatomic variability of the patella and femur [24,25]. However, in order to determine the effects of pathologies a consistent means of

quantifying changes must be established and this requires a consistent way to quantify “normal” anatomy and kinematics.

25 There have been several attempts to quantify errors in coordinate system creation and to standardize aspects of its application, but no standard definition has been proposed and implemented by the biomechanics community. Bull *et al.* investigated various methods of describing patellofemoral motion and also compared the kinematic outcomes of using two different femoral flexion and long axis definitions [1]. However, the effect
30 of the variation of the patellar coordinate system was not investigated. Several investigators have quantified the repeatability [2,12,26-28] and sensitivity [11] of the creation of their particular patellar coordinate systems. Katchburian *et al.* [29] conducted a thorough review of patellar kinematics and recommended the coordinate system described by Lafortune [30] as being the ‘most useful’, possibly because it follows the
35 method suggested by Grood and Suntay [31]. However, this is the only direct comparison of a range of coordinate systems in the literature to date.

Within the clinical community several studies have examined inter- and intra-observer variability of patellar measures such as sulcus angle, congruence angle, patellar height, patellar axis, lateral patellofemoral angle, lateral patellar tilt [32-34].

40 Unfortunately, these measures do not describe three-dimensional kinematics, and therefore cannot fully characterize patellar motion.

Selection of appropriate landmarks that allow for coordinate system creation is important. Landmarks should be defined without ambiguity and it should be possible to digitize them repeatably. The landmarks for an *in vitro* study, which may involve
45 disarticulation of the joint, may not be appropriate for an *in vivo* study. The use of

palpation *in vivo* may yield different results to those obtained from an imaging study.

Additionally, imaging modalities, such as computed tomography (CT) [35,36] and magnetic resonance imaging (MRI) scans [8,18,19,37-39] are increasingly being employed to measure patellar kinematics. The locations of the required landmarks may be digitized from these scans using two- or three-dimensional imaging techniques. Two dimensional techniques are prone to projection errors due to the alignment of the subject within the imaging device [40], and therefore it would seem that three-dimensional measures would be preferable.

The selection of a preferred coordinate system should provide, at the very least, a repeatable way to quantify kinematics, allowing the same reference frames to be employed for a range of subjects, thereby facilitating comparisons between them. In addition, as mentioned by Wu *et al.*, clinically relevant kinematic results, which can be used to interpret the movements of the bones in a meaningful way, are preferable [41].

Therefore, in this study the research questions were:

- What are the intra- and inter-investigator repeatabilities of the digitization of anatomic landmarks on the patella from MRI images?
- What are the effects of varying the patellar coordinate system definition on the resulting *in vivo* three-dimensional patellofemoral kinematics?
- Is there one patellar coordinate system definition that is preferable over all others for use with imaging techniques?

2. Methods

2.1 Subjects and imaging

Ten normal subjects with no history of knee pain, injury, osteoarthritis, surgery, or contraindication to MRI were recruited to participate in this study (4 female, 6 male, 34 ± 6 yrs, 70.8 ± 15.8 kg). Institutional ethics board approval was obtained and each subject provided informed consent. A initial MRI scan was acquired in the sagittal plane with the subject's knee in a relaxed position using a 3T MRI scanner (Intera, Phillips, Best, The Netherlands) and the following parameters: 0.586mm in-plane resolution, 300mm field of view, 2mm slice separation, 512 x 512 matrix size, 360ms repetition time, 10.0ms echo time, 90° flip angle, knee MRI coil. Subject-specific bone models of the femur and patella were created from this scan [42]. Six additional MRI scans were then acquired in the sagittal plane with the following parameters: 1.25mm in-plane resolution, 320mm field of view, 7mm slice separation, 256 x 256 matrix size, 307ms repetition time, 6.2ms echo time, 90° flip angle, body MRI coil. For each scan the subject's knee was placed in one of six flexion angles, ranging from 0° to 50°, in increments of 10°, with a load of 15% bodyweight applied to the foot [42]. To determine the joint angles from the loaded scans, the bone models were registered to the images using an Iterative Closest Points algorithm implemented in Matlab (The MathWorks, Natick, MA, USA) [42].

2.2 Landmark digitization

Digitization of landmarks from the high-resolution scans was performed using Analyze 8.1 (Analyze Direct Inc, Overland Park, KS, USA) image processing software. The locations of seven landmarks on the bony surface of the patella were digitized and the locations of three additional points were calculated (Table 2, Fig. 1). Landmarks were selected only if they were applicable to an *in vivo* analysis (i.e. they could be determined through palpation and/or imaging techniques). The insertions of the

quadriceps and patellar tendons were not included for this reason, although they have been used in the literature. Possible origin locations were selected from among those that were previously used in the literature for being well defined, applicable to an *in vivo* analysis, and based solely on patellar landmarks.

95 The position of each digitized landmark was identified by a single point selection. Intra-investigator variability was established by having one investigator digitize the patellar landmarks of three subjects on five separate occasions. Inter-investigator variability was quantified by having four other participants digitize the same landmarks on the same three subjects. All participants were given the same set of written
100 instructions to follow and were asked to record all intermediate data, such as the calculation of a mid-slice location. The variability of the digitized landmarks and calculated locations was represented by the mean of the three radii defining the smallest ellipsoid that contained all of the points with a tolerance of 1×10^{-6} mm [43].

2.3 Coordinate system variation

105 To determine how differences in the patellar coordinate system axes affect three-dimensional kinematics, four different patellar axis definitions were applied to each subject. The landmarks that were selected as the basis of the flexion and long axes for each coordinate system are listed in Table 3. For each definition the cross product of the long axis and the flexion axis yielded the third, anteriorly-pointing axis. The cross
110 product was again applied to the third axis and the long axis to obtain an orthogonal flexion axis. Positive directions for the right-handed coordinate systems were proximal, lateral, and anterior, respectively. Rotations about the three axes were found using a modified Joint Coordinate System convention [8,44]. The origin was the same for all

patellar coordinate systems and was based upon landmarks chosen according to the

115 repeatability results of the previous section. Each coordinate system was applied to both the two- and three-dimensional digitizations, resulting in a total of eight coordinate system trials.

In order to facilitate the comparison of the patellar coordinate systems, a single femoral coordinate system was created for each subject, with a flexion axis between the
120 most posterior points on the femoral condyles, and the long axis from the centre of the femur at the midshaft to the centre of the shaft above the condyles. Again, two cross products were applied to obtain an orthogonal right-handed coordinate system, the first between the long and flexion axes, and the second between the third and long axes. The origin for the femoral coordinate system was the most proximal point of the intercondylar
125 notch [15].

2.4 Landmark and coordinate system comparisons

The repeatabilities of intra- and inter-investigator digitizations were compared by ranking the means of the three radii defining the smallest ellipsoid that contained all of the selections of a particular landmark [43]. The repeatabilities of potential locations for
130 the patellar coordinate system origin were ranked in a similar way. Variability of the kinematic quantities was defined as the standard deviations of flexion, spin, and tilt over all six knee flexion angles for the three repeatedly measured subjects. To establish the effect of choosing a different coordinate system on the kinematic outcomes the mean absolute differences between resultant rotations were calculated for the full ranges of
135 motion of all ten subjects. In addition, we tested the hypothesis that coordinate system

definition changed joint kinematics using Wilcoxon signed rank tests and Spearman rank correlation coefficients (SRCCs). Significant differences were defined as $p < 0.05$.

3. Results

3.1 Landmark digitization

140 The patellar landmark with the least intra- and inter-investigator variability was the most distal point in both two (Dist-2) and three dimensions (Dist-3; Table 2). In terms of inter-investigator variability only, in three dimensions the second and third least variable landmarks were the most lateral point on the patella (Lat-3) and the most distal point on the patellar spine (Dist.Spine-3). The landmark with the most intra- and inter-
145 investigator variability in three dimensions was the most posterior point on the patella (Post-3). Based upon these results, when digitizations were performed in three dimensions, it would be expected that the first coordinate system definition (3D-1) would be the most repeatable. In two dimensions the second and third least variable landmarks were the most distal (Dist.Spine-2) and most proximal (Prox.Spine-2) points on the
150 patellar spine.

 The origin location with the least intra- and inter-investigator variability in three dimensions was the centre of the most proximal, distal, medial, and lateral points (Centre-3; Table 2). In two dimensions, the most repeatable point was the midpoint of the most proximal and distal points of the patellar spine (Prox.Dist-2).

3.2 Coordinate system variation

155 As anticipated from the results of the landmark digitizations, in three dimensions 3D-1 produced the least variable results overall (Fig. 2). In two dimensions 2D-1 and 2D-2 had the least variability in kinematic output. A representative set of coordinate

systems are shown in Figure 3. The greatest differences in mean kinematic angles were
160 between coordinate systems 3D-2 and 3D-3 with average differences of 11.5° in flexion,
5.0° in spin, and 27.3° in tilt (Table 4); however, statistically significant differences were
found between many of the coordinate systems. The only pair with no significant
differences between two and three dimensions was 2D-2 and 3D-2. Despite this, SRCCs
amongst coordinate systems in two or three dimensions revealed excellent agreement
165 between all coordinate system definitions in flexion in both ($\text{SRCC} \geq 0.970$), as well as in
spin and tilt in two dimensions ($\text{SRCC} \geq 0.881$ and 0.903 respectively). Low agreement
was found in spin and tilt in three dimensions ($\text{SRCC} \geq 0.445$ and ≥ 0.622 respectively).
SRCCs between coordinate systems in two and three dimensions using the same
landmarks showed the highest agreement between 2D-1 and 3D-1 ($\text{SRCC} = 0.996$ in
170 flexion, 0.792 in spin, and 0.920 in tilt).

4. Discussion

We assessed the effects of varying the patellar coordinate system definition on
patellofemoral kinematic quantities and the intra- and inter-investigator repeatabilities of
the digitization of anatomic landmarks on the patella from MRI images because a
175 standard coordinate system for the patella has yet to be proposed or adopted. Our results
show clearly that the choice of anatomic landmarks can result in large changes in the
resultant patellar rotations with respect to the femur. It is therefore not surprising that
results have varied greatly in the literature, even in studies of healthy individuals [29]. It
is likely that even more variation would be observed in pathological joints, where
180 landmarks may not have the same relative positions; this makes it all the more important
to standardize the patellar coordinate system in studies of pathological joints..

In general, the intra- and inter-investigator repeatabilities of landmark digitization were comparable to previous studies. The average radii of the points selected by five investigators were on the same order as, and generally less than, those found by a similar study that examined landmarks of the scapula [43]. These results are also on the same order as those of Ahmed *et al.* and Belvedere *et al.*, who quantified the variability of their respective patellar coordinate system definitions in cadaveric specimens [2,12]. As would be expected, intra-observer repeatability was better than inter-observer repeatability, so if possible a single investigator should perform all digitization for a given study.

The choice of coordinate system had a substantial effect on three-dimensional patellar kinematic quantities and their repeatability. The differences in kinematic quantities between coordinate systems were much larger than anticipated, with the greatest differences observed in tilt. The differences were clearly associated with differences in the landmarks used to define their axes. For example, the patellofemoral flexion angle was dictated by the landmarks that were selected to define the long axis, and patellofemoral tilt was affected by flexion axis definition. These correspondences were also found by Morton *et al.* in their probabilistic analysis examining the sensitivity of patellofemoral kinematics to anatomical landmark locations in a cadaver model [28]. The large differences emphasize the importance of standardizing the patellar coordinate system.

The most suitable coordinate system for any given application is generally the one that yields the least variability, and the choice will be dictated by whether the measurements are made in two or three dimensions. For three dimensional

205 measurements, 3D-1 is recommended, to minimize confounding errors. To maintain consistency, the use of 2D-1 is similarly recommended when digitizations are to be performed in two dimensions. The differences between the resultant kinematic angles from these two coordinate system definitions in two and three dimensions are small and their agreement is high, as demonstrated by the SRCCs. The origin location should also
210 be the point with the least variability, namely Centre-3 in three dimensions and Centre-2-3 in two dimensions.

The use of a single digitizing modality may be viewed as a limitation; however, the aim of this study was not to compare software packages, and these results are considered to be representative of what would be expected in an MRI-based study. In
215 addition, the use of mathematical models to determine coordinate systems automatically was not addressed. Due to their automated nature, it is expected that the repeatability would be high; however, as noted previously, in particular when using a bounding box method the alignment of the axes are affected by the alignment of the subject within the scanner. It has been noted that certain joint pathologies may alter the shape of the patella
220 and this might affect the identification of the landmarks described herein. This study examined only healthy participants in order to establish a benchmark of reliability.

Strengths of this study include a thorough quantification of the repeatability of digitizing patellar landmarks *in vivo*, the production of a framework for comparing data between studies using various patellar coordinate system definitions, and the proposal of
225 a standardized, repeatable patellar coordinate system.

The methods proposed here focused on the definition of the patella coordinate frame itself and how it affects resultant kinematics. The recommended anatomic

coordinate frame may be employed in the calculation of dynamic in vivo patellar kinematics when used in combination with any method that reliably quantifies patellar motion. For example, MRI may be used to obtain a detailed model of the patella, on which the coordinate axes could be established, and which could then be registered to fluoroscopic images of the patella in motion.

5. Conclusion

In conclusion, we recommend a standard patellar coordinate system with an intermediary flexion axis defined between the most medial and lateral points of the patella, a superiorly-directed long axis defined between the most proximal and distal points on the patella, an anteriorly-directed axis that is the result of a cross product of these first two axes, and a final laterally-directed flexion axis that is the result of the cross product of the superior and anterior axes. The origin should lie at the centre of the most proximal, distal, medial, and lateral points. This would minimize kinematic measurement variability caused by landmark selection and allow better comparisons of results reported by differing research groups.

6. Conflict of interest statement

There are no commercial or personal relationships with any other persons or organizations that may lead to conflicts of interest.

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Fig. 1. Anatomical landmarks that were digitized on the patella (see also Table 2). The (A) sagittal mid-slice was found by calculating the slice that lay midway between the most medial and most lateral slices in the sagittal plane in which the patella was visible. The (B) axial mid-slice was found by calculating the slice that lay midway between the most proximal and most distal slices in the axial plane in which the patella was visible.

Fig. 2. (A) Intra- and (B) inter-investigator repeatability. Mean (± 1 SD) repeatability for five trials, across all subjects, for eight different patellar coordinate systems (Table 3) paired with a single femoral coordinate system.

Fig. 3. Representative sample of the femoral coordinate system, and four patellar coordinate systems created with two-dimensional point digitization. F and P indicate the patellar coordinate system; subscripts F, L and T represent the flexion, long and third axes. The modified Joint Coordinate System axes are e1, e2 (indicated by asterisk) and e3. Patellar coordinate systems 2D 1 through 4 are shown in magenta, cyan, blue and green, respectively. The patellar long axes are coincidental for coordinate systems 1 and 3, and 2 and 4 (as indicated by the dashed line); as a result the floating axes of these pairs of coordinate systems are also coincidental (as indicated by the dashed line with the asterisk).

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455 Table 1. Landmarks used in the literature to create anatomical coordinate systems on the patella and femur.

	Femur	Patella
Flexion Axis	<p>Line joining medial and lateral epicondyles [2-6]</p> <p>Line joining medial and lateral posterior points of condyles [7-9]</p> <p>Line joining centres of spheres fit to femoral condyles [10,11]</p> <p>Plane touching posterior condyles [12]</p> <p>Parallel to tibial coordinate system at full extension [13]</p>	<p>Line joining posterior point and lateral point [9,18]</p> <p>Line joining medial and lateral points [8,11]</p> <p>Parallel to femoral axis at full extension [3]</p> <p>Parallel to femoral axis at 90° [12]</p> <p>Parallel to tibial coordinate system at full extension [13]</p>
Long Axis	<p>Anatomical (between two points along femoral shaft) [1]</p> <p>Anatomical (origin along centre of femoral shaft) [4,6,7,10,11]</p> <p>Mechanical (origin to centre of femoral head) [2,3]</p> <p>Trochlear (line along deepest portion of trochlear groove) [12]</p> <p>Parallel to tibial coordinate system at full extension [13]</p>	<p>Line joining proximal and distal points [7,8,18]</p> <p>Posterior flat edge [19,20]</p> <p>Perpendicular to flexion and third [11]</p> <p>Parallel to femoral axis at full extension [3]</p> <p>Parallel to femoral axis at 90° [12]</p> <p>Parallel to tibial coordinate system at full extension [13]</p> <p>Between origin and distal point [2]</p> <p>Line connecting insertions of quadriceps and patellar tendons [10]</p>
Third Axis	<p>Perpendicular to flexion/extension and long axes [2,3,10]</p> <p>Parallel to tibial coordinate system at full extension [13]</p>	<p>Perpendicular to flexion and long axes [10]</p> <p>Cross product of medial lateral axis and vector from inferior apex along anterior surface [11]</p> <p>Parallel to femoral axis at full extension [3]</p> <p>Parallel to femoral axis at 90° [12]</p> <p>Parallel to tibial coordinate system at full extension [11]</p> <p>Perpendicular to plane containing medial, lateral and distal points [2]</p>
Origin	<p>Deepest point of the trochlear groove where it meets the intercondylar notch [8,14]</p> <p>Most proximal point of the intercondylar notch [15]</p> <p>Most posterior point on the sulcus groove in the axial plane [9]</p> <p>Proximal point of intercondylar notch along to anatomical axis [12]</p> <p>Centre of the intercondylar notch [13]</p> <p>Midpoint between medial and lateral epicondyles [3,16]</p>	<p>Posterior point on axial midslice [8,9]</p> <p>Midpoint of line joining medial and lateral points of patella [2,11]</p> <p>Centre of the patella [3,6,7,12,14,21]</p> <p>Centre of the patella using most proximal, distal, medial and lateral points [7]</p> <p>Centre of the patellar ridge [13]</p> <p>Projection of centre of patella onto line connecting insertions of quadriceps and patellar tendons [10]</p> <p>Geometric centre [16]</p>

	Midpoint of centres of spheres fit to femoral condyles [10,11] Intersection between the screw axis of the femur (helical axis) and the sagittal plane bisecting the knee [17] Centre of the posterior cruciate ligament insertion [6]	Aligned with femur at full extension [3]
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460 Table 2. Points that were digitized and calculated on the patella, listed with the intra-and inter-investigator repeatabilities of landmark selection.

Description	Abbreviation	Intra-investigator	Inter-investigator
		Mean $\pm$ 1SD	Mean $\pm$ 1SD
		(mm)	(mm)
Most medial point selected on the axial midslice	Med-2	0.17 $\pm$ 0.12	0.63 $\pm$ 0.32
Most medial point selected in three dimensions	Med-3	0.50 $\pm$ 0.10	0.91 $\pm$ 0.08
Most lateral point selected on the axial midslice	Lat-2	0.20 $\pm$ 0.10	0.76 $\pm$ 0.43
Most lateral point selected in three dimensions	Lat-3	0.43 $\pm$ 0.02	0.65 $\pm$ 0.21
Most proximal point selected on the sagittal midslice	Prox-2	0.37 $\pm$ 0.07	0.44 $\pm$ 0.08
Most proximal point selected in three dimensions	Prox-3	0.37 $\pm$ 0.25	0.84 $\pm$ 0.27
Most distal point selected on the sagittal midslice	Dist-2	0.11 $\pm$ 0.02	0.27 $\pm$ 0.20
Most distal point selected in three dimensions	Dist-3	0.34 $\pm$ 0.04	0.60 $\pm$ 0.09
Most proximal point of patellar spine selected on the sagittal midslice	Prox.Spine-2	0.30 $\pm$ 0.21	0.29 $\pm$ 0.08
Most proximal point of patellar spine selected in three dimensions	Prox.Spine-3	0.55 $\pm$ 0.06	0.97 $\pm$ 0.39
Most distal point of patellar spine selected on the sagittal midslice	Dist.Spine-2	0.21 $\pm$ 0.19	0.28 $\pm$ 0.18
Most distal point of patellar spine selected in three dimensions	Dist.Spine-3	0.52 $\pm$ 0.42	0.79 $\pm$ 0.30
Most posterior point selected on the axial midslice	Post-2	0.33 $\pm$ 0.05	0.46 $\pm$ 0.11
Most posterior point selected in three dimensions	Post-3	0.70 $\pm$ 0.88	1.67 $\pm$ 0.85
Midpoint of Med-2 and Lat-2	Med.Lat-2	0.20 $\pm$ 0.06	0.49 $\pm$ 0.08
Midpoint of Med-3 and Lat-3	Med.Lat-3	0.34 $\pm$ 0.09	0.63 $\pm$ 0.24
Midpoint of Prox-2 and Dist-2	Prox.Dist-2	0.25 $\pm$ 0.11	0.29 $\pm$ 0.08
Midpoint of Prox-3 and Dist-3	Prox.Dist-3	0.35 $\pm$ 0.13	0.53 $\pm$ 0.18
Centre of Med-2, Lat-2, Prox-2, and Dist-2	Centre-2	0.17 $\pm$ 0.07	0.32 $\pm$ 0.03
Centre of Med-3, Lat-3, Prox-3, and Dist-3	Centre-3	0.24 $\pm$ 0.07	0.44 $\pm$ 0.15

465 Table 3. Landmarks used in the creation of the initial flexion and long axes for the four
patellar coordinate system definitions.

Name	Flexion axis	Long axis
2D-1	Med-2 and Lat-2	Prox-2 and Dist-2 [11,18]
2D-2	Med-2 and Lat-2	Prox.Spine-2 and Dist.Spine-2
2D-3	Post-2 and Lat-2	Prox-2 and Dist-2 [11,18]
2D-4	Post-2 and Lat-2	Prox.Spine-2 and Dist.Spine-2
3D-1	Med-3 and Lat-3 [8,11]	Prox-3 and Dist-3 [7,8]
3D-2	Med-3 and Lat-3 [8,11]	Prox.Spine-3 and Dist.Spine-3
3D-3	Post-3 and Lat-3 [9,18]	Prox-3 and Dist-3 [7,8]
3D-4	Post-3 and Lat-3 [9,18]	Prox.Spine-3 and Dist.Spine-3

470 Table 4. Mean (± 1 SD) absolute differences in the resultant kinematic angles between
the eight patellar coordinate systems (listed in Table 3) for all subjects across six knee
flexion angles. Comparisons are shown within the two-dimensional approaches, within
the three-dimensional approaches, and between the two- and three-dimensional
approaches that used the same landmarks for coordinate system creation. Significant
differences ($p < 0.05$) are indicated by a star (*).

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Flexion (°)	2D-1	2D-2	2D-3	2D-4	3D-1	3D-2	3D-3
2D-2	10.8 $\pm$ 3.5*						
2D-3	0.0 $\pm$ 0.0	10.8 $\pm$ 3.5*					
2D-4	10.8 $\pm$ 3.5*	0.0 $\pm$ 0.0	10.8 $\pm$ 3.5*				
3D-1	1.0 $\pm$ 1.2*						
3D-2		1.4 $\pm$ 1.5			11.5 $\pm$ 3.0*		
3D-3			1.0 $\pm$ 1.2*		0.0 $\pm$ 0.0	11.5 $\pm$ 3.0*	
3D-4				1.4 $\pm$ 1.5	11.5 $\pm$ 3.0*	0.0 $\pm$ 0.0	11.5 $\pm$ 3.0*

Spin (°)	2D-1	2D-2	2D-3	2D-4	3D-1	3D-2	3D-3
2D-2	1.5 $\pm$ 1.5						
2D-3	0.0 $\pm$ 0.0	1.5 $\pm$ 1.5					
2D-4	1.5 $\pm$ 1.5	0.0 $\pm$ 0.0	1.5 $\pm$ 1.5				
3D-1	3.4 $\pm$ 2.3						
3D-2		3.5 $\pm$ 3.1			5.0 $\pm$ 3.8		
3D-3			3.4 $\pm$ 2.3		0.0 $\pm$ 0.0	5.0 $\pm$ 3.8	
3D-4				3.5 $\pm$ 3.1	5.0 $\pm$ 3.8	0.0 $\pm$ 0.0	5.0 $\pm$ 3.8

Tilt (°)	2D-1	2D-2	2D-3	2D-4	3D-1	3D-2	3D-3
2D-2	1.0 $\pm$ 0.8*						
2D-3	21.1 $\pm$ 2.4*	22.1 $\pm$ 2.6*					
2D-4	20.3 $\pm$ 2.5*	21.2 $\pm$ 2.4*	0.9 $\pm$ 0.7*				
3D-1	2.5 $\pm$ 1.4*						
3D-2		1.9 $\pm$ 1.1			1.8 $\pm$ 1.6*		
3D-3			5.7 $\pm$ 4.8*		25.5 $\pm$ 5.8*	27.3 $\pm$ 6.2*	
3D-4				3.3 $\pm$ 2.6*	22.2 $\pm$ 2.4*	24.0 $\pm$ 2.9*	4.7 $\pm$ 1.5*