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Soft-tissue artefact assessment during step-up using fluoroscopy and skin-mounted markers

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Abstract

When measuring knee kinematics with skin-mounted markers, soft tissue and structures surrounding the knee hide the actual underlying segment kinematics. Soft-tissue artefacts can be reduced when plate-mounted markers or marker trees are used instead of individual unconstrained mounted markers. The purpose of this study was to accurately quantify the soft-tissue artefacts and to compare two marker cluster fixation methods by using fluoroscopy of knee motion after total knee arthroplasty during a step-up task.

Ten subjects participated 6 months after their total knee arthroplasty. The patients were randomised into (1) a plate-mounted marker group and (2) a strap-mounted marker group. Fluoroscopic data were collected during a step-up motion. A three-dimensional model fitting technique was used to reconstruct the in vivo 3-D positions of the markers and the implants representing the bones.

The measurement errors associated with the thigh were generally larger (maximum translational error: 17 mm; maximum rotational error 12°) than the measurement errors for the lower leg (maximum translational error: 11 mm; maximum rotational error 10°). The strap-mounted group showed significant more translational errors than the plate-mounted group for both the shank (respectively, 3 ± 2.2 and 0 ± 2.0 mm, $p=0.025$) and the thigh (2 ± 2.0 and 0 ± 5.9 mm, $p=0.031$). The qualitative conclusions based on interpretation of the calculated estimates of effects within the longitudinal mixed-effects modelling evaluation of the data for the two groups (separately) were effectively identical. The soft-tissue artefacts across knee flexion angle could not be distinguished from zero for both groups. For all cases, recorded soft-tissue artefacts were less variable within subjects than between subjects.

The large soft-tissue artefacts, when using clustered skin markers, irrespective of the fixation method, question the usefulness of parameters found with external movement registration and clinical interpretation of stair data in small patient groups.

Keywords: Soft-tissue artefacts; Fluoroscopy; Stair; Kinematics; Total knee arthroplasty

1. Introduction

To identify causes for knee dysfunction, related to diagnosis, treatment, rehabilitation programs and prosthesis design, a complete understanding of knee kinematics is necessary (Ramsey and Wretenberg, 1999). The most widely accepted non-invasive method to study knee kinematics is stereophotogrammetry using skin-mounted markers (Leardini et al., 2005). However, soft tissue and structures surrounding the knee interfere with the actual underlying kinematics. Task-dependent displacements of individual skin-mounted markers relative to the underlying bone of more than 20 mm are reported (Cappozzo et al., 1996; Fuller et al., 1997; Holden et al., 1997; Manal et al., 2000; Sati et al., 1996a, b; Stagni et al., 2005). The location

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of the skin-mounted markers is another important factor influencing the error (Della Croce et al., 2005; Sati et al., 1996b). Soft-tissue artefacts can be reduced when plate-mounted markers or marker trees—defining the individual body segments—are used instead of individual unconstrained mounted markers (Manal et al., 2000). In addition to gait data, stair data are often used in kinematical studies since stair climbing provides an approximation to other activities involving the flexed knee under high load during daily activities.

The most accurate measurement technique for in vivo performance of total knee replacement prosthesis is 3-D fluoroscopic analysis (Banks and Hodge, 2004; Dennis et al., 1998). The position and orientation of 3-D computer models of total knee components are manipulated so that their projections on the image match those captured during the in vivo knee motion. If tantalum markers are used as alternative for standard skin-based markers, this technique can be used to determine the accuracy of skin-mounted marker fixation systems (Garling et al., 2005).The purpose of this study was to accurately quantify the soft-tissue artefacts and to compare two marker cluster fixation methods by using fluoroscopy of subjects after total knee arthroplasty during a step-up task.

2. Materials and methods

Ten patients were included 6 months after a total knee arthroplasty (Table 1). Inclusion criteria were the ability to perform a step-up task without the help of bars or a cane, scored ‘none’ or ‘slight’ in the Knee Society pain score during activity. Exclusion criteria were a functional impairment of any other lower extremity joint besides the operated knee, the use of walking aids and the inability to walk more than 500 m. The institutional medical-ethical committee approved the study and all subjects gave written informed consent.

The patients were randomised into two groups: (1) a plate-mounted (PM) marker group and (2) a strap-mounted (SM) marker group. The PM group received contour-moulded Thermoplast marker-plates containing six 3-mm stainless steel beads, mimicking the normally used reflecting markers, at the lateral side of the femur (14 × 24 cm) and the medial-frontal border of the tibia (12 × 24 cm). The marker plates were attached with Velcro straps (Fig. 1a). To create a fluoroscopic depiction, the plates had extensions with marker-configurations (4 × 4 × 3 cm polystyrene blocs containing six 2-mm stainless steel beads) attached to them.

The SM group received two polystyrene squares (4 × 4 × 3 cm) attached to elastic straps containing six 2-mm RVS beads. The straps were positioned at the distal part of the lateral femur and at the proximal part of the lateral tibia (Fig. 1b).

Reversed engineered models of the tibia component and the femoral component were used to assess the poses of the femur and the tibia bones assuming that the components were fixed in the bones (Kaptein et al., 2003).

Table 1
Anthropometric data for the two groups (median, min–max)

	Plate-mounted group ($n = 5$)	Strap-mounted group ($n = 5$)
Age (years)	75, 65–82	71, 53–79
BMI (kg/m^2)	30, 27–35	29, 26–34
Sex (F/M)	3/2	3/2

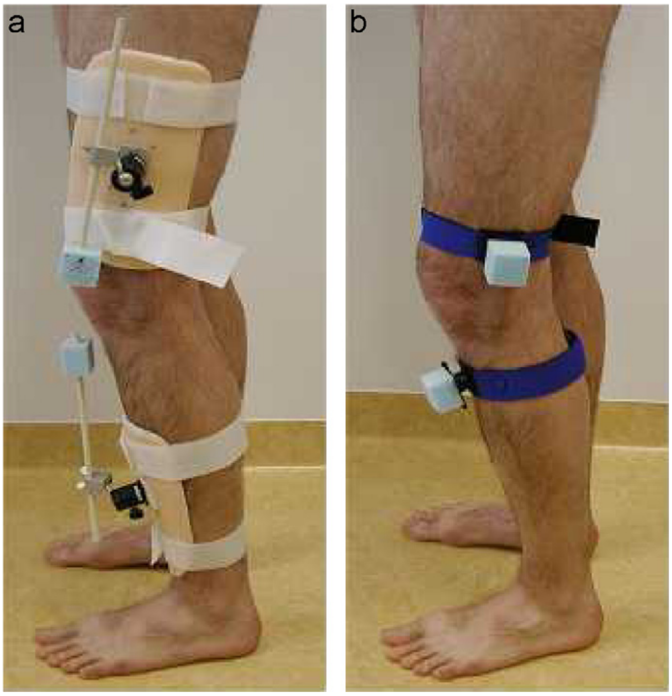

Fig. 1. The plate-mounted marker configuration with adjustable extensions for visualisation (a). Strap-mounted marker configurations in the polystyrene blocs (b).

2.1. Experimental set-up

The patients were asked to perform a step-up task in front of the fluoroscope. The step-up platform (riser height 18 cm) was centred between the image intensifier and the focus of the fluoroscope. The patients’ knee was positioned in front of the image intensifier. The height of the image intensifier was adjusted to the height of the patient by centring the field of view at the lateral side of the joint cavity of the knee. The patients were asked to perform the step-up task in a controlled manner without the use of holding bars. At the start of the step-up, the leg with the total knee prosthesis was positioned on top of the step-up. The step-up was finished when the contra-lateral leg was on top of the step-up. The patient performed five step-ups in total, the first two step-ups were used to gain comfort with the experimental set-up and during the last three runs, data were collected.

2.2. Data analysis

Prior to measurements, the fluoroscopic set-up (Super Digital Fluorography (SDF) system, Toshiba Infinix-NB: Toshiba, Zoetermeer, The Netherlands) was calibrated. To calibrate the fluoroscopic system and to correct for image distortion, an image run of 3 s of a specially designed calibration box (BAAT Engineering B.V., Hengelo, The Netherlands) was made before each experiment (15 frames/s; 1024 × 1024 image matrix; pulse width of 1 ms).

The 2-D positions of the marker projections in the fluoroscopy images were automatically detected with an algorithm based on the Hough-transformation for circle detection (Duda and Hart, 1972). For obtaining a more accurate location of each 2-D marker projection, a parabolic model of the marker is fitted to the marker’s grey value profile (Vrooman et al., 1998). Marker configuration model-based roentgen fluoroscopic analysis (Medis specials, Leiden, The Netherlands) was used to estimate the pose of the marker configurations from this 2-D data (Garling et al., 2005). This method requires the 3-D models of the defined rigid bodies. To assess 3-D models of the marker configurations of both the strap markers

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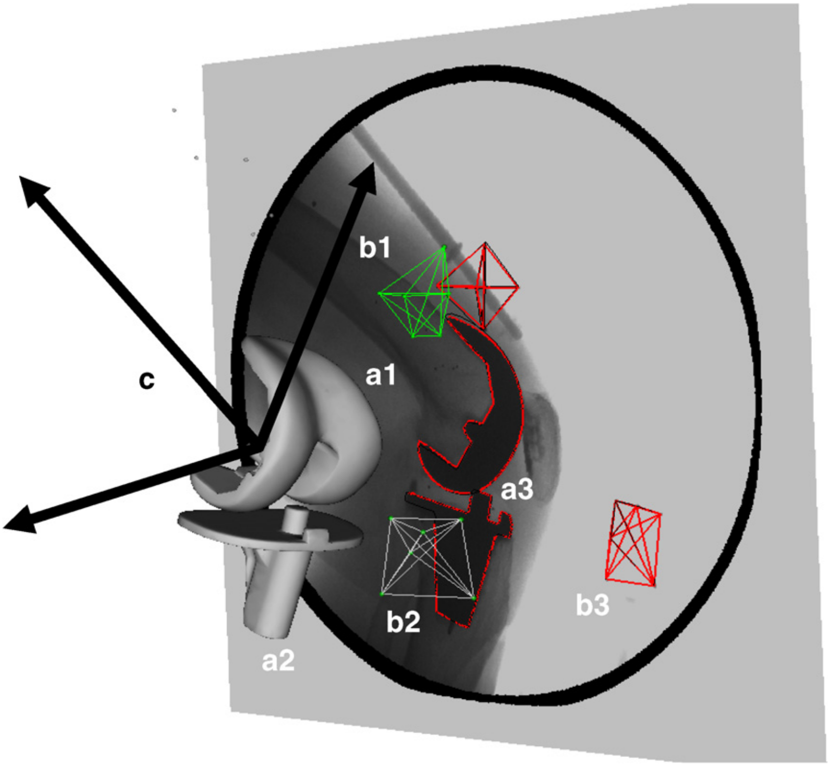

Fig. 2. An analysed fluoroscopic image of the PM group showing the reversed engineered models of the femoral component (a1), and tibial component (a2) and their 2-D projections (a3). In addition, the marker configuration models of the plate-mounted markers on the femur (b1), tibia (b2) and their 2-D projections are visible (b3). The orientation of the coordinate system is defined by the local coordinate system of the femoral component (c).

and the marker plate markers, two Roentgen stereophotogrammetric analysis (RSA) radiographs were made directly after the measurements and analysed using RSA-CMS software (Medis, Leiden, The Netherlands). These radiographs were also used to assess the relationship between the marker-configurations at the marker plates and the marker-configurations at the extensions.

The coordinate system was defined by the local coordinate system of the femoral component (Fig. 2). Positive directions of rotations about these axes followed the right-hand rule. Since prostheses are placed using alignment instrumentation, this local coordinate system is highly reproducible between subjects. The plate markers and the strap markers of the thigh and shank were defined with respect to this coordinate system.

With the assessed 3-D positions of the bones, strap markers and plate markers, the relative rotations about all axes of the shank with respect to the thigh were calculated with extension (0°) as the reference (Söderkvist and Wedin, 1993). Positive directions for rotations about the coordinate axes were defined as posterior tilt, external rotation and valgus rotation.

The measurement error, i.e., soft-tissue artefact was defined as the difference between the joint rotations of the bones and the joint rotations of the strap or plate markers.

2.3. *Statistical analysis*

The non-parametric Mann–Whitney *U*-test was used to compare the differences in anthropometric data between the SM group and the PM group. For all statistical analyses, significance was set as a *p*-value of less than 0.05.

For both knee internal–external rotation and knee joint adduction–abduction, a linear mixed-effects model for longitudinal data was used for analysis, augmented with a penalised spline with within-patient random (spline) effect to evaluate and adjust for possible deviation from the linear effects assumption. We refer to Durban et al. (2005) for a full description of the model and data-analytic approach (Durban et al., 2005). The model assumes a subject-specific linear trend of observed outcome (internal–external rotation and adduction–abduction of the knee joint) with knee flexion angle and adds a patient-specific penalised spline to counter for possible subject-specific non-linear deviation from the global linear trend. For the linear component of the model, results may be summarised through the population intercept and slope of the global linear trend (i.e. the population mean) as well as within and between patient-specific random effects for slope and intercept. With respect to the non-linear (spline) component of the model, it was found that fitted effects were effectively zero and may, therefore, be ignored from any further qualitative interpretation or discussion of results.

3. Results

The measurement errors associated with the thigh, presented in Table 2, were generally larger (maximum translational error: 17 mm; maximum rotational error 12°) than the measurement errors for the lower leg (maximum translational error: 11 mm; maximum rotational error 10°). The SM group showed significant more translational errors than the PM group for both the shank (respectively, 3 ± 2.2 and 0 ± 2.0 mm, $p=0.025$) and the thigh (2 ± 2.0 and 0 ± 5.9 mm, $p=0.031$). Rotational errors up to 12° were found for the SM group.

However, it is more important to assess how the soft-tissue artefact propagates to knee arthrokinematics. Especially the non-sagittal plane joint movements are of interest. In Figs. 3 and 4, the difference between the bone and the SM and PM markers for knee joint internal–external rotation

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and adduction–abduction are presented. During higher flexion angles, the internal–external rotation of the shank was over-estimated by the skin-mounted marker groups. During extension, the internal–external rotation error between skin and bone decreased. In two cases in the PM group, the skin markers under-estimated the actual internal–external rotation of the shank. In general, the adduction–abduction of the shank was over-estimated by the skin-mounted marker groups.

From a qualitative point of view, the calculated summary estimates (systematic linear population effect, within and between patient estimates and variability) are identical (Table 3). The mean population deviation (as longitudinal trend) could not be distinguished from zero (linear population effect) for both groups. For all cases, the errors were less variable within subjects, than between subjects. Taking the small sample size in the current study into account, we must, therefore, conclude that the studied effect is either small, or absent.

Table 2
Relative motion of the plate- and strap-mounted markers with respect to the underlying bone

	Shank		Thigh	
	Translations (mm)	Rotations (deg)	Translations (mm)	Rotations (deg)
Plate				
Mean	−0.1	0.4	0.2	−0.4
SD	2.0	1.8	5.9	2.9
Min	−6.9	−8.3	−17.4	−10.2
Max	10.9	9.6	16.6	5.2
Strap				
Mean	3.0	−0.8	1.8	−0.7
SD	2.2	2.8	2.0	3.7
Min	−0.8	−7.2	−1.6	−11.8
Max	8.3	3.6	7.5	7.7

Paradoxical movements were registered when, e.g., the movement of the plate-mounted markers was compared with the underlying bone kinematics. For instance, Fig. 5 shows an external rotation of the tibia with respect to the femur while the plate markers show a movement pattern that can be compared with the screw-home phenomenon or external rotation of the tibia in extension with internal rotation as the angle of flexion increases. In the first phase of extension, the plate markers attached to the tibia rotate internally, while in the end phase, these plate markers rotate externally.

There was no relationship between body mass index (BMI) and the error in knee angles for either group.

4. Discussion

To avoid the error component of soft-tissue artefacts in kinematic analyses, kinematic data have been obtained via invasive techniques (Fuller et al., 1997; Ramsey and Wretenberg, 1999), exoskeletal attachment systems (Ganjikia et al., 2000; Sati et al., 1996a), computed tomography (Hagemeister et al., 1999), magnetic resonance imaging (Patel et al., 2004), elimination of this error through mathematical correction (Lucchetti et al., 1998; Sati et al., 1996b), RSA and fluoroscopy (Banks and Hodge, 1996; Fantozzi et al., 2003). However, not all of these techniques are applicable to study knee kinematics because of disadvantages like risk of infection (especially applicable after TKA), pain, loss in freedom of movement, high exposure to radiation, or the inaccuracy of the method.

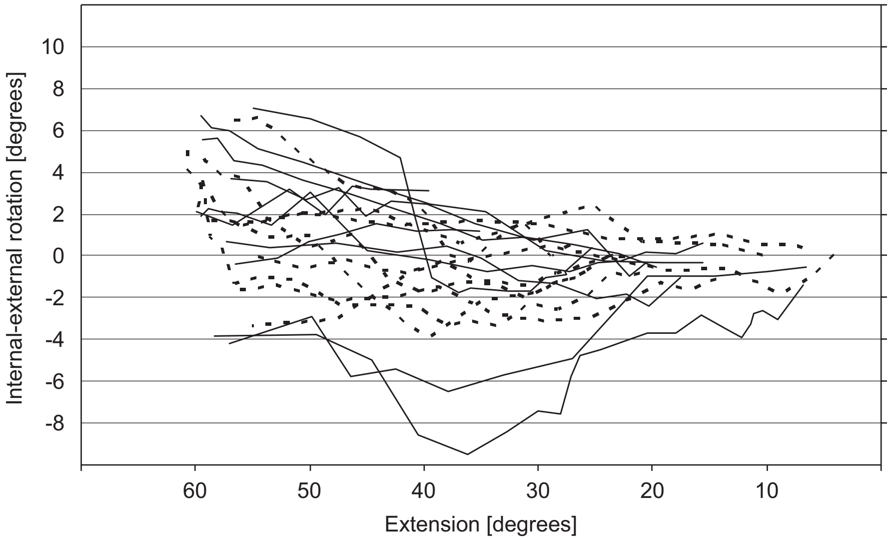

Fig. 3. Difference between the bone and either plate (-) or strap (- -) mounted markers resulting in internal–external rotation of the shank with respect to the thigh. Positive values describe an over-estimation, zero describes perfect agreement and negative values describe an under-estimation of the skin-mounted marker-derived knee joint rotations.

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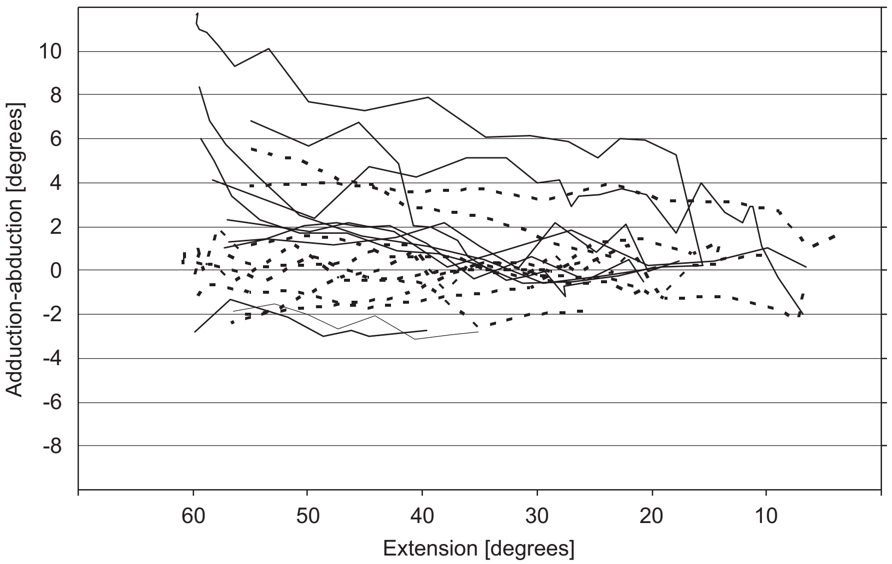

Fig. 4. Difference between the bone and either plate (-) or strap (- -) mounted markers resulting in adduction–abduction of the shank with respect to the thigh. Positive values describe an over-estimation, zero describes perfect agreement and negative values describe an under-estimation of the skin-mounted marker-derived knee joint rotations.

Table 3
Summary of the calculated estimates of the linear effect

	Plates (deg)			Straps (deg)		
	Estimate	Standard error	Confidence interval	Estimate	Standard error	Confidence interval
Internal–external rotation						
Intercept	8.22	25.80	−42.92:59.09	−2.66	21.68	−45.67:39.28
Slope	0.28	0.61	−0.90:1.48	−0.02	0.53	−1.06:1.01
Reproducibility intercept	0.75			0.68		
Reproducibility slope	0.93			0.93		
Standard error within patient effect intercept	0.61	0.18	0.34:1.01	0.65	0.20	0.34:1.10
Standard error within patient effect slope	0.15	0.01	0.13:0.17	0.15	0.01	0.12:0.17
Standard error between patient effect intercept	1.06	0.62	0.40:2.62	0.94	0.51	0.38:2.25
Standard error between patient effect slope	0.55	0.23	0.29:1.13	0.54	0.23	0.28:1.12
Adduction–abduction						
Intercept	17.48	25.20	−32.07:67.17	0.14	18.60	−36.75:37.18
Slope	0.28	0.60	−0.89:1.45	−0.02	0.44	−0.89:0.83
Reproducibility intercept	0.53			0.64		
Reproducibility slope	0.93			0.95		
Standard error within patient effect intercept	1.03	0.54	0.37:2.35	0.62	0.17	0.35:0.99
Standard error within patient effect slope	0.15	0.01	0.13:0.18	0.12	0.01	0.11:0.15
Standard error between patient effect intercept	1.09	0.70	0.39:2.88	0.83	0.41	0.37:1.98
Standard error between patient effect slope	0.54	0.22	0.28:1.11	0.52	0.19	0.28:1.00

Fluoroscopy seems to be the most accurate and accepted method to study kinematics after total knee replacement. Fluoroscopic data can be utilised in an experimental environment to validate kinematic acquisition methods or validate dynamic models of body segments. However, besides the patients' exposure to radiation, it would not be practical as a clinical tool due to the limitation of analysis to a single joint and the extensive image data processing. Optimising the use of stereophotogrammetric systems and providing insight into the measurement accuracy would, therefore, be the goal to aim for. The most appealing solution to correct for the skin-movement error would be to filter out the contaminating soft-tissue movement. However, no regular systematic pattern of marker displacement was found in this study for both of the marker attachment methods. Absence of a regular pattern was also reported in several other studies (Holden et al., 1997; Manal et al., 2003; Sati et al., 1996b). The absence of a

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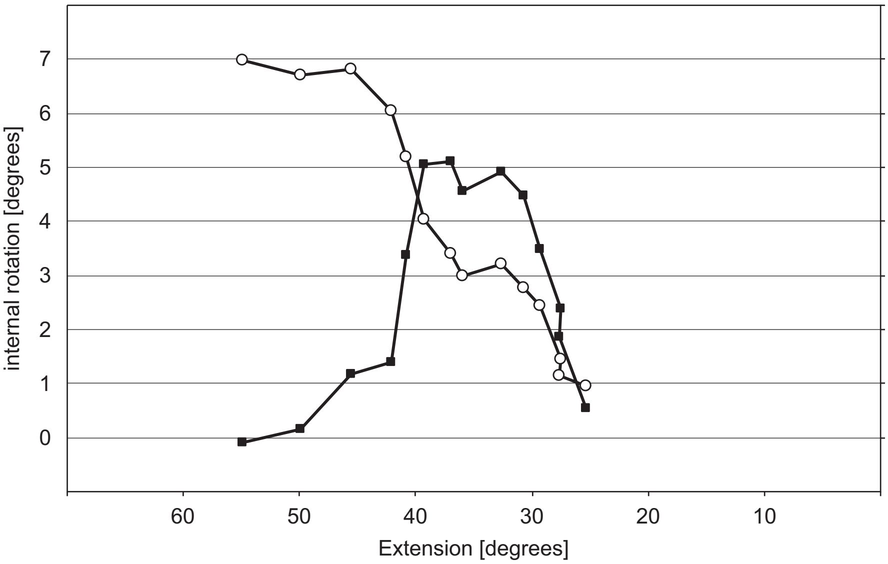

Fig. 5. Example of an individual subject showing a paradoxical internal–external rotation of plate-mounted markers (■) and the underlying prosthesis (○) of the tibia with respect to the femur.

regular pattern makes accurate mathematical correction of marker positions impossible. The frequency content of the soft tissue moving relative to the bones lies within the same spectra as the actual motion of the bones itself (Fuller et al., 1997; Stagni et al., 2005). Next to this, several in vivo kinematic studies of TKA have demonstrated that femorotibial kinematics in itself is not predictable in patients with a total knee prosthesis (Banks and Hodge, 2004; Dennis et al., 1998; Hill et al., 2000).

Most studies quantifying soft-tissue artefacts used walking, running or cycling as the motor task for healthy subjects. It can be concluded from these studies that there is—like in the present study—a large variability between subjects and in the task performed. Therefore, it is not possible to compare the error found with the marker attachment methods used in this study with the errors found in the literature. An explanation for the variability between subjects in this study might be deviations in orientation of the femoral component from the actual epicondylar axis after implantation despite the use of alignment instrumentation (Chauhan et al., 2004). This will cause deviations between subjects in the reference local coordinate system defined by the femoral component.

Two other studies have also used fluoroscopy to quantify the skin movement artefacts. Cappozzo et al. (1996) compared the movement of anatomical skin markers during walking and movement of the external fixation devices patients had due to a fracture of the tibia or femur. They reported skin-marker displacements of up to 40 mm and rotations of 4–10° and 6–20° with respect to the tibia and femur, respectively. Anatomical landmarks were used as reference, thereby introducing another source of error (Della Croce et al., 2005). This might explain the larger displacements compared to our study. Sati et al. (1996a) compared individual skin markers and geometric parameters of the bone to quantify skin movement on the femur during dynamic flexion. Maximal ranges of the soft-tissue artefacts in the in-plane directions found were 42.5 and 20 mm. The use of a simplified fluoroscopic technique and the use of unconstrained markers might explain the differences with the current study.

Further study, including expanding the patient group, may reveal systematic errors allowing mathematical correction for skin artefacts in specific tasks that were not found in this study due to the small sample size and inherently large between-subject variability. A recently developed technique for fluoroscopy using digital reconstructed radiographs will provide accurate data of the in vivo kinematics of healthy subjects in the near future (Mahfouz et al., 2005). A database of this accumulated data may provide accurate dynamic models and insight in skeletal kinematics.

5. Conclusion

The large soft-tissue artefacts when using clustered skin markers, irrespective of the fixation method, question the usefulness of parameters found with external movement registration and clinical interpretation of stair data in small patient groups. Results of femorotibial kinematics derived from skin-mounted markers during a stair task should be interpreted and presented within the margin of error presented in this study.

References

Banks, S.A., Hodge, W.A., 1996. Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Transactions on Biomedical Engineering 43, 638–649.

Please cite this article as: Garling, E.H., et al., Soft-tissue artefact assessment during step-up using fluoroscopy and skin-mounted markers. Journal of Biomechanics (2007), doi:10.1016/j.jbiomech.2007.03.003

Banks, S.A., Hodge, W.A., 2004. Implant design affects knee arthroplasty kinematics during stair-stepping. Clinical Orthopedics 426, 187–193.

Cappozzo, A., Catani, F., Leardini, A., Benedetti, M.G., Della Croce, U., 1996. Position and orientation in space of bones during movement: experimental artefacts. Clinical Biomechanics 11, 90–100.

Chauhan, S.K., Scott, R.G., Breidahl, W., Beaver, R.J., 2004. Computer-assisted knee arthroplasty versus a conventional jig-based technique. A randomised, prospective trial. Journal of Bone and Joint Surgery (British) 86 (3), 372–377.

Della Croce, U., Leardini, A., Chiari, L., Cappozzo, A., 2005. Human movement analysis using stereophotogrammetry Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. Gait and Posture 21 (2), 226–237.

Dennis, D.A., Komistek, R.D., Colwell, C.E., Ranawat, S.C., Scott, R.D., et al., 1998. In vivo anteroposterior femorotibial translation of total knee arthroplasty: a multicenter analysis. Clinical Orthopedics 356, 47–57.

Duda, R.O., Hart, P.E., 1972. Use of the Hough transformation to detect lines and curves in pictures. Comunications of the ACM, 11–15.

Durban, M., Harezlak, J., Wand, M.P., Carroll, R.J., 2005. Simple fitting of subject-specific curves for longitudinal data. Statistics in Medicine 24, 1153–1167.

Fantozzi, S., Benedetti, M.G., Leardini, A., Banks, S.A., Cappello, A., Assirelli, D., Catani, F., 2003. Fluoroscopic and gait analysis of the functional performance in stair ascent of two total knee replacement designs. Gait and Posture 17, 225–234.

Fuller, J., Liu, L.J., Murphy, M.C., Mann, R.W., 1997. A comparison of lower-extremity skeletal kinematics measured using skin and pin-mounted markers. Human Movement Sciences 16, 219–242.

Ganjikia, S., Duval, N., Yahia, H., de Guise, J., 2000. Three-dimensional knee analyzer validation by simple fluoroscopic study. The Knee 7, 221–231.

Garling, E.H., Kaptein, B.L., Geleijns, K., Nelissen, R.G.H.H., Valstar, E.R., 2005. Marker configuration model based Roentgen fluoroscopic analysis. Journal of Biomechanics 38 (4), 893–901.

Hagemeister, N., Yahia, H., Duval, N., de Guise, J., 1999. In vivo reproducibility of a new non-invasive diagnostic tool for three-dimensional knee evaluation. The Knee 6, 175–181.

Hill, P.F., Williams, V.V., Iwaki, H., Pinskerova, V., Freeman, M.A.R., 2000. Tibiofemoral movement 2: the loaded and unloaded living knee studied by MRI. Journal of Bone Joint Surgery (British) 82, 196–1200.

Holden, J.P., Orsini, J.A., Lohmann Siegel, K., Kepple, T.M., Gerber, L.H., Stanhope, S.J., 1997. Surface movement errors in shank kinematics and knee kinetics during gait. Gait and Posture 5, 217–227.

Kaptein, B.L., Valstar, E.R., Stoel, B.C., Rozing, P.M., Reiber, J.H., 2003. A new model-based RSA method validated using CAD models and models from reversed engineering. Journal of Biomechanics 36, 873–882.

Leardini, A., Chiari, L., Croce, U.D., Cappozzo, A., 2005. Human movement analysis using stereophotogrammetry Part 3. Soft tissue artifact assessment and compensation. Gait and Posture 21 (2), 212–225.

Lucchetti, L., Cappozzo, A., Cappello, A., Della Croce, U., 1998. Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics. Journal of Biomechanics 31, 977–984.

Mahfouz, M.R., Hoff, W.A., Komistek, R.D., Dennis, D.A., 2005. Effect of segmentation errors on 3D-to-2D registration of implant models in X-ray images. Journal of Biomechanics 38 (2), 229–239.

Manal, K., McClay, I., Stanhope, S., Richards, J., Galinat, B., 2000. Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. Gait and Posture 11, 38–45.

Manal, K., McClay Davis, I., Galinat, B., Stanhope, E., 2003. The accuracy of estimating proximal tibial translation during natural cadence walking: bone vs skin mounted targets. Clinical Biomechanics 8, 126–131.

Patel, V.V., Hall, K., Ries, M., Lotz, J., Ozhinsky, E., Lindsey, C., Lu, Y., Majumdar, S., 2004. A three-dimensional MRI analysis of knee kinematics. Journal of Orthopaedic Research 22, 283–292.

Ramsey, D.K., Wretenberg, P.F., 1999. Biomechanics of the knee: methodological considerations in the in vivo kinematic analysis of the tibiofemoral and patellofemoral joint. Clinical Biomechanics 14, 595–611.

Sati, M., de Guise, J.A., Larouche, S., Drouin, G., 1996a. Improving in vivo knee kinematic measurements: application to prosthetic ligament analysis. The Knee 3, 179–190.

Sati, M., de Guise, J.A., Larouche, S., Drouin, G., 1996b. Quantitative assessment of skin-bone movement at the knee. The Knee 3, 121–138.

Söderkvist, I., Wedin, P.A., 1993. Determining the movements of the skeleton using well-configured markers. Journal of Biomechanics 26, 1473–1477.

Stagni, R., Fantozzi, S., Cappello, A., Leardini, A., 2005. Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects. Clinical Biomechanics 20 (3), 320–329.

Vrooman, H.A., Valstar, E.R., Brand, G.J., Admiraal, D.R., Rozing, P.M., Reiber, J.H., 1998. Fast and accurate automated measurements in digitized stereophotogrammetric radiographs. Journal of Biomechanics 31, 491–498.

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