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Quantification of soft tissue artefact in motion analysis by combining 3D fluoroscopy and stereophotogrammetry: a study on two subjects

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Abstract

Background. Soft tissue artefact is the most invalidating source of error in human motion analysis using optoelectronic stereophotogrammetry. It is caused by the erroneous assumption that markers attached to the skin surface are rigidly connected to the underlying bones. The quantification of this artefact in three dimensions and the knowledge of how it propagates to relevant joint angles is necessary for the interpretation of gait analysis data.

Methods. Two subjects, treated by total knee replacement, underwent data acquisition simultaneously with fluoroscopy and stereophotogrammetry during stair climbing, step up/down, sit-to-stand/stand-to-sit, and extension against gravity. The reference 3D kinematics of the femur and tibia was reconstructed from fluoroscopy-based tracking of the relevant prosthesis components. Soft tissue artefact was quantified as the motion of a grid of retro-reflecting makers attached to the thigh and shank with respect to the underlying bones, tracked by optoelectronic stereophotogrammetry. The propagation of soft tissue artefact to knee rotations was also calculated.

Findings. The standard deviation of skin marker trajectory in the corresponding prosthesis-embedded anatomical frame was found up to 31 mm for the thigh and up to 21 mm for the shank. The ab/adduction and internal/external rotation angles were the most affected by soft tissue artefact propagation, with root mean square errors up to 192% and 117% of the corresponding range, respectively.

Interpretations. In both the analysed subjects the proximal thigh showed the largest soft tissue artefact. This is subject- and task-specific. However, larger artefact does not necessarily produce larger propagated error on knee rotations. Propagated errors were extremely critical on ab/adduction and internal/external rotation. These large errors can nullify the usefulness of these variables in the clinical interpretation of gait analysis.

Keywords: Human motion analysis; Soft tissue artefact; Knee kinematics; Fluoroscopy; Stereophotogrammetry

1. Introduction

The description of human joint kinematics during daily living activity is the main aim of human motion analysis. Stereophotogrammetry allows for the reconstruction of the trajectories of markers or fixtures, on which markers are mounted, attached to the skin surface of the body segments to be analysed. These trajectories are used to calculate the pose of the underlying bony segments, with the erroneous assumption that markers and bony segments are rigidly connected. It is well known that markers on the surface of the body move with respect to the underlying bones because of the interposition of soft tissues. This interposition is the origin of two different sources of error: anatomical

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Nomenclature

Angles and directions:
Ab/Ad abduction/adduction
Fl/Ex flexion/extension
In/Ex internal/external rotation
AP antero-posterior
Long longitudinal
ML medio-lateral

Marker cluster combinations:
ThT–ShT total cluster on the thigh and total cluster on the shank
ThP–ShT proximal cluster on the thigh and total cluster on the shank
ThC–ShT central cluster on the thigh and total cluster on the shank
ThD–ShT distal cluster on the thigh and total cluster on the shank
ThD–ShD distal cluster on the thigh and distal cluster on the shank

Motor tasks:
EG extension against gravity
STS sit-to-stand/stand-to-sit
SUD step up/down
SC stair climbing

Others:
RMS root mean square
STA soft tissue artefact

landmarks mislocation and soft tissue artefact (STA). The latter has been recently recognized to be the major source of error in human motion analysis (Andriacchi and Alexander, 2000). Because of its origin STA is necessarily associated to the specific marker-set and experimental protocol adopted. Inertial effects, skin deformation and sliding, gravity and muscle contraction interdependently contribute to this phenomenon. This artefact has a frequency content similar to that of bone movement and is therefore not possible to distinguish between them by means of any filtering technique. A quantification of STA is thus necessary in order to critically consider motion analysis results and indications for the clinical decision process, and to develop methods for STA compensation to improve bone pose estimation accuracy.

Several studies have been performed to quantify the motion of skin markers with respect to underlying bony segments using intracortical pins (Cole et al., 1993; Fuller et al., 1997; Karlsson and Lundberg, 1994; Lafortune, 1984; Lafortune and Lake, 1991; Lafortune et al., 1992; Levens et al., 1948; Reinschmidt et al., 1997a,b; Westblad et al., 2000; Yack et al., 2000), external fixators (Angeloni et al., 1992; Cappozzo et al., 1996), percutaneous trackers (Holden et al., 1997; Manal et al., 2000; Manal et al., 2002) and Roentgen photogrammetry (Maslen and Ackland, 1994; Sati et al., 1996; Tranberg and Karlsson, 1998). All these previous attempts to quantify STA have important limitations. Intracortical pins, external fixators and percutaneous trackers provide a reliable measurement of bony segment motion, but they limit and alter skin motion. Methods exploiting Roentgen photogrammetry, either X-ray pictures or fluoroscopy, do not limit skin motion, but they do not usually allow for a full 3D tracking of skin markers. Even when 3D trajectories (Sati et al., 1996) can be estimated, the very limited fluoroscopic field of view confines the trackable markers to small areas around the joints. In particular, X-ray pictures allow for the description of STA in 2D only and in static conditions and not during the execution of motor tasks. The wide range of techniques used, the different motor tasks analysed, and the limitations observed in these experiments are likely to have caused the large discrepancies reported in these studies.

The purpose of the present study was to quantify STA on the thigh and shank of two subjects by an innovative technique which combines traditional stereophotogrammetry with modern 3D-kinematics reconstruction from fluoroscopic images. This technique gives a reliable and complete description of STA in body segments, in unconstrained skin conditions and during the execution of motor tasks typical of daily living. The extent to which STA propagates to knee rotation angles was also assessed in order to determine the effect of STA on relevant kinematic variables routinely reported. The results obtained for the two subjects were then compared and discussed, in order to point out differences and similar behaviours observed.

2. Methods

2.1. Subjects

Two female subjects treated by total knee replacement were analysed. The subjects had clinically successful knee arthroplasty (excellent Hospital for Special Surgery score 85–100, (Insall et al., 1976)) and gave informed consent to participate in this study. The age, height, weight and Body Mass Index and follow-up of subject #1 and #2 were 67 and 64 years, 155 and

164 cm, 58 and 60 kg, 24 and 22 kg/m^2, and 18 and 25 months, respectively.

2.2. Experimental set-up and methodology

In order to assess the amount of STA of the lateral aspect of the thigh and shank, a cluster of reflecting skin markers was attached to each segment. The clusters were 4–5 cm spaced grids of markers with a diameter of 0.6 cm. Nineteen and twenty-five markers were uniformly attached laterally on the skin of the thigh of subject #1 and #2, respectively. Ten skin markers were also attached to the lateral aspect of the shank. Moreover, one rigid plate with four markers was attached to the pelvis using a modified Milwaukee orthosis (Benedetti et al., 1998). A sketch of the marker distribution on the subjects is shown in Fig. 1.

Five additional specialized reflecting and radiopaque markers, therefore visible to stereophotogrammetric and fluoroscopic systems, with a diameter of 1.2 cm were used. Four of these (Fig. 2E) were placed on a plane parallel to the image plane of the fluoroscope (Fig. 2B) for spatial registration of the two measurement systems. The fifth specialized reflecting and radiopaque marker was attached to the skin over the patella for temporal synchronization (Fig. 2F).

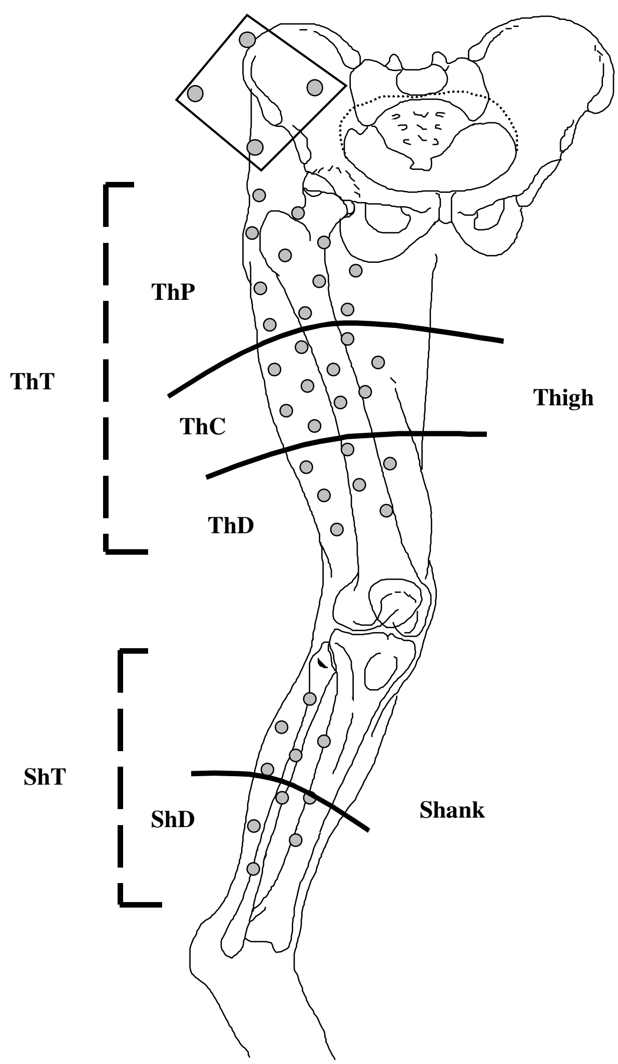

Fig. 1. Skin marker distribution on thigh and shank and separation in proximal, central, distal sub-clusters and total cluster.

A static up-right posture was acquired. The position of 10 anatomical landmarks (right and left anterior iliac spines, sacrum, greater trochanter, lateral and medial epicondyles, tibial tuberosity, head of fibula, lateral and medial malleoli) was calibrated with respect to the relevant cluster of markers (Benedetti et al., 1998). Data from the two subjects were acquired during stair climbing (SC), step up/down (SUD), sit-to-stand/stand-to-sit (STS), and knee extension against gravity (EG) activities by fluoroscopy and stereophotogrammetry simultaneously. EG activity was performed in up-right posture with the hip held flexed at approximately 45°. Two repetitions were collected for each activity. The subjects performed each motor task with the knee under analysis inside the fluoroscopic 32 cm field of view. The cameras of the stereophotogrammetric system were then placed around the fluoroscope to track all the reflecting markers throughout the entire motor task.

The marker trajectories were collected at 50 frames per second by means of a stereophotogrammetric system with 5 TV cameras (Smart, e-Motion, Padova, Italy). The stereophotogrammetric calibrated field of view was $1.5 \times 1.5 \times 1$ m.

2.3. Data analysis

The 3D kinematics of pelvis, thigh and shank was reconstructed using the CAST experimental protocol (Cappozzo et al., 1995), relevant anatomical reference frames were defined accordingly (Benedetti et al., 1998). For the thigh, four different clusters of skin markers were considered (Fig. 1): proximal (P), central (C), distal (D) subsets and total (T = P + C + D). Two different clusters were considered for the shank: total (T) and distal (D). The position and orientation in space of each cluster were reconstructed using the Singular Value Decomposition algorithm (Soderkvist and Wedin, 1993). The hip joint centre position was calculated through anatomical regression equations (Bell et al., 1989).

The 3D pose (position and orientation) of the prosthesis components was reconstructed by means of the 2D fluoroscopic projections and CAD models of the prosthesis components. Series of images were acquired at nominal 6 samples per second with a standard fluoroscope (DRS, System 1694 D, General Electric CGR, Issy-les-Moulineaux, France). The images were printed out on films and digitised by means of a scanner (Scanmaster DX, Howtek, Hudson, NH, USA). Moreover,

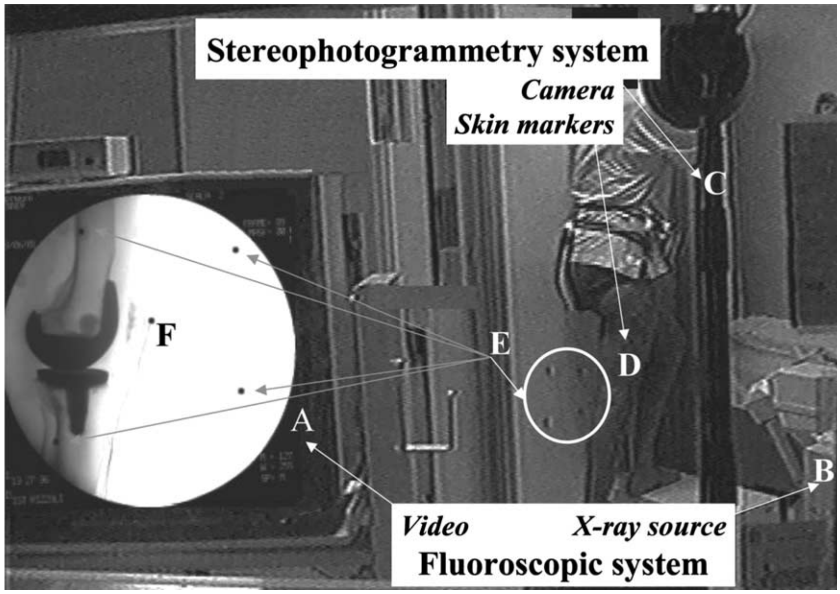

Fig. 2. Experimental set-up. (A) Real-time visible feed-back of the fluoroscopic images acquired. (B) X-rays source of the fluoroscope. (C) One of the five cameras of the stereophotogrammetric system. (D) Skin markers on the lateral aspect of the thigh and the shank. (E) The four specialized radiopaque/reflecting markers for spatial registration. (F) The specialized radiopaque/reflecting marker for temporal synchronization.

images of a 3D cage of plexiglas with 18 tantalum balls in known positions and of a rectangular grid of lead balls 10 mm apart were collected in order to calculate respectively the position of the camera focus and the parameters necessary for image distortion correction. This was obtained using a global spatial warping technique (Gronenschild, 1997). An established technique for 3D kinematics analysis of a known object from a single view was implemented (Banks and Hodge, 1996). Prosthesis component poses in space were obtained from each fluoroscopic image by an iterative procedure using a technique based on CAD-model shape matching. Previous validation work (Banks and Hodge, 1996) had shown that orientation and position of each component in the sagittal plane can be estimated with accuracy better than 1° and 0.5 mm, respectively.

Accuracy tests were replicated for this study. The femoral and tibial components of the same prosthesis implanted in the subjects of the present study (Optetrak PS-cemented, Exactech Inc., Gainesville, FL, USA) were fixed in an unknown relative pose using bone-cement. Fluoroscopic images were taken in five different positions within the field of view. The relative pose of the two components in each image was estimated using the method described. These estimates were compared with the ones obtained by a 3D digitizer (MicroScribe 3D × 3D Digitizer, Immersion, San Jose, CA, USA), with nominal accuracy of 0.2 mm. The femoral component was held fixed to a workbench and the coordinates of about 38 000 and 23 000 points were collected on both the femoral and tibial component surfaces, respectively. The Iterative Closest Point technique (Besl and McKay, 1992) was used for surface rigid registration between the points digitized and the relevant prosthesis component CAD model. Then, the relative pose between the two registrated CAD models was calculated. The results showed that the accuracy with which relative orientation and position of the components can be estimated is better than 1.5° and 1.5 mm respectively, as good as those previously obtained (Banks and Hodge, 1996).

Spatial registration between the stereophotogrammetric and fluoroscopic measurement systems was obtained by defining a common absolute reference frame by means of the four radiopaque and reflecting markers. The temporal synchronization was obtained by matching the fluoroscopic trajectories with the resampled stereophotogrammetric ones of the fifth specialized marker. The matching was obtained by calculating the maximum cross-correlation between the two trajectories, considering the resampling frequency and the starting frame as the parameters to be determined. Skin marker trajectories obtained from the stereophotogrammetric system and the 3D poses of the prosthesis components obtained from 3D fluoroscopy were then transformed in the absolute reference frame.

The possible misalignment of the prosthesis components with respect to the relevant anatomical reference frame was calculated in the static up-right posture, considered as reference position. This misalignment, if present, is due to surgery. The fluoroscopy-based 3D pose of the anatomical reference frame was calculated accordingly.

The skin marker trajectories along the antero/posterior (AP), medio/lateral (ML) and longitudinal (Long) directions on the thigh and shank were then reported in the corresponding bone embedded anatomical frame.

The standard deviation of the position of each marker in the relevant anatomical reference frame was calculated for each motor task and each subject.

Knee rotations were calculated according to Grood and Suntay convention (1983) from the 3D kinematics of anatomical reference frames obtained from fluoroscopy and stereophotogrammetry: flexion/extension (Fl/Ex) is assumed as the rotation of the shank about the medio-lateral anatomical axis of the thigh, internal/external (In/Ex) rotation about the longitudinal axis of the shank, abduction/adduction (Ab/Ad) about the axis orthogonal to the former two at each frame. Knee rotation angles calculated from fluoroscopy were assumed as the "gold standard". Stereophotogrammetry-based knee rotations were calculated using different technical frames based on possible combinations of skin marker clusters: complete thigh and complete shank (ThT–ShT), proximal thigh and complete shank (ThP–ShT), central thigh and complete shank (ThC–ShT), distal thigh and complete shank (ThD–ShT), distal thigh and distal shank (ThD–ShD). The Root Mean Square (RMS) difference between knee rotations evaluated from skin markers and 3D fluoroscopy in percentage of their corresponding range for all motor tasks, was calculated for each combination of clusters.

In order to assess how STA directly influenced the orientation of the marker clusters, the orientation of the total cluster technical frame in the corresponding fluoroscopy-based anatomical reference frame was calculated. This is shown by the standard deviation of the rotations according to Euler XYZ convention.

3. Results

Skin markers were found to move considerably with respect to the corresponding underlying bony segment. In Fig. 3, 3D marker trajectories are reported in the sagittal plane of the corresponding anatomical reference frame during the execution of the STS motor task for subject #1.

The shank showed an overall smaller amount of STA than the thigh, according to the standard deviation of the position of the skin markers on the thigh and shank in the corresponding anatomical reference frame (Fig. 4). The maximum artefact observed on the shank had a standard deviation of 20.6 mm in EG task along the ML direction for subject #1 and of 16.3 mm in SC task along the Long direction for subject #2. For the thigh, the amount of STA was definitely higher for both subjects, with a maximum of 21.4 mm in STS task for subject #1 and of 31.1 mm in SC task for subject #2 along the ML direction (see Supplementary Table 1).

The displacement of the skin markers on the shank was larger than the one on the thigh along the AP anatomical direction during the EG task in both subjects (Fig. 5). Displacement of shank skin markers was larger than on the thigh also along the Long direction during SC for subject #1 only.

The ML displacement of skin markers was largest on the postero-lateral area of the thigh for most motor tasks in both subjects. This result can be appreciated in Fig. 6, in particular for the SUD motor task.

The Long displacement of skin markers was largest on the postero-proximal area of the thigh for most

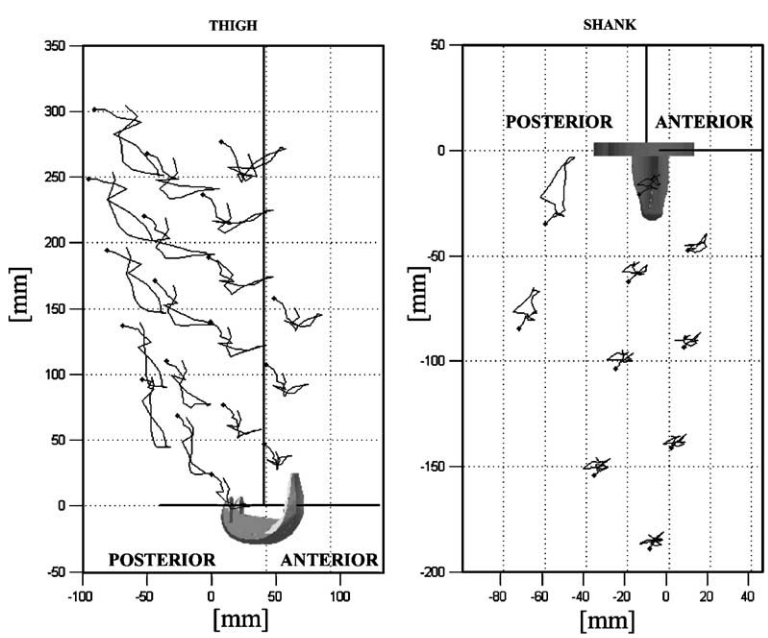

Fig. 3. Sagittal view of skin marker trajectories in the corresponding bone-embedded anatomical frames for the thigh and shank, for subject #1 during the execution of STS motor task.

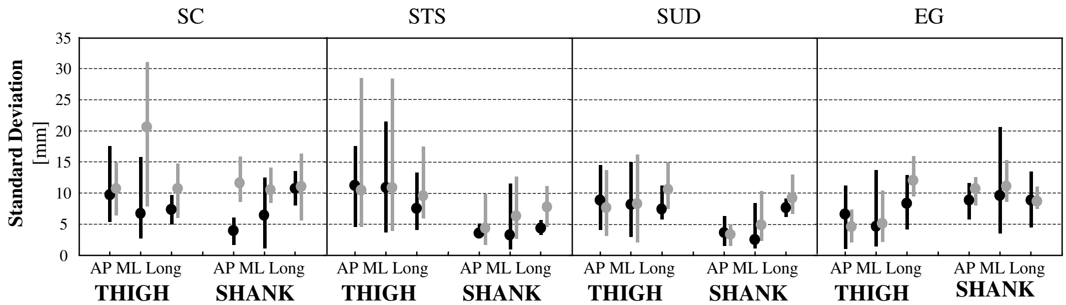

Fig. 4. Bar plot of the minimum–maximum range (bar) and mean value (circle) (mm) of the standard deviation of the skin markers along the antero-posterior, medio-lateral and longitudinal anatomical directions over the thigh and shank of the two subjects analysed (#1 in black and #2 in grey). Values are reported for the SC, STS, SUD and EG motor tasks. The numerical data are reported in Table 1 provided as on-line additional material.

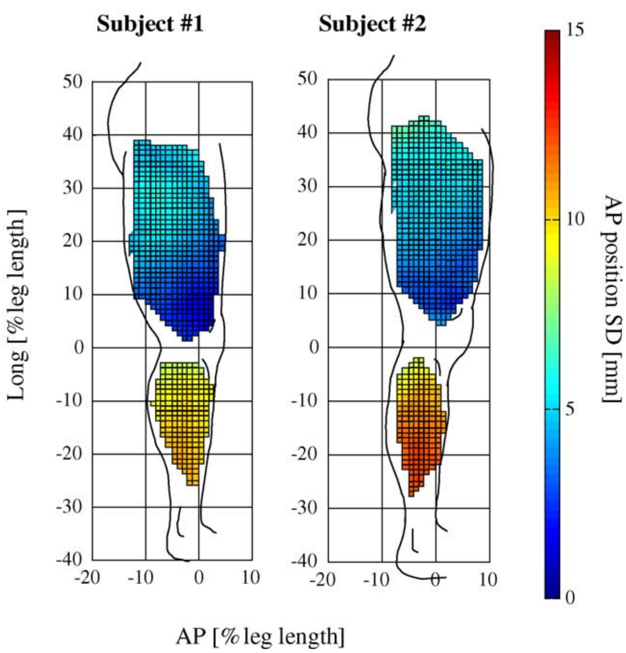

Fig. 5. Mapping of the standard deviation of the marker positions along the antero-posterior anatomical direction on the thigh and shank of subject #1 and #2 during the execution of the EG motor task. Distances along the antero-posterior (AP) and longitudinal axis (Long) are expressed in percentage of the leg length of the specific subject. A sketchy depiction of the leg of the subject is superimposed.

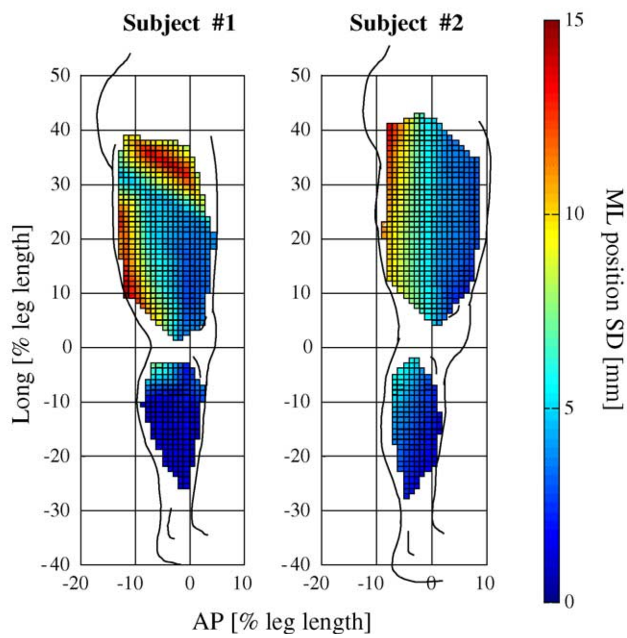

Fig. 6. Mapping of the standard deviation of the marker positions along the medio-lateral anatomical direction on the thigh and shank of subject #1 and #2 during the execution of the SUD motor task. Distances along the antero-posterior (AP) and longitudinal axis (Long) are expressed in percentage of the leg length of the specific subject. A sketchy depiction of the leg of the subject is superimposed.

motor tasks in both subjects. This result is shown in Fig. 7 in particular for the STS motor task.

When different clusters of skin markers were chosen for the reconstruction of the kinematics of bony segments, large discrepancies in knee rotations were observed. In Fig. 8, it can be qualitatively observed that Ab/Ad and In/Ex are more affected by STA than Fl/Ex, and are critically dependent on cluster selection. The position indicated by the arrows, in which all curves almost coincide, is the one closest to the anatomical landmark calibration configuration, thus showing the smallest propagated error. As soon as the subject moves from the calibration position the propagated error gets larger.

The strong dependency of STA propagation to knee rotations on the cluster selection is demonstrated by data reported in Fig. 9. The RMS difference of knee rotations between the gold standard and those evaluated with each cluster combination expressed in percentage of the corresponding range is reported. In particular, the Fl/Ex is always the least affected by STA with respect to its range. RMS difference reaches a maximum of 17.2% (SUD task, ThP–ShT clusters) and 23.4% (STS task, ThP–ShT clusters) for subjects #1 and #2, respectively. The Ab/Ad angle is much more affected by STA, with RMS difference up to 191.8% (SUD task, ThP–ShT clusters) and 70.5% (STS task, ThD–ShT

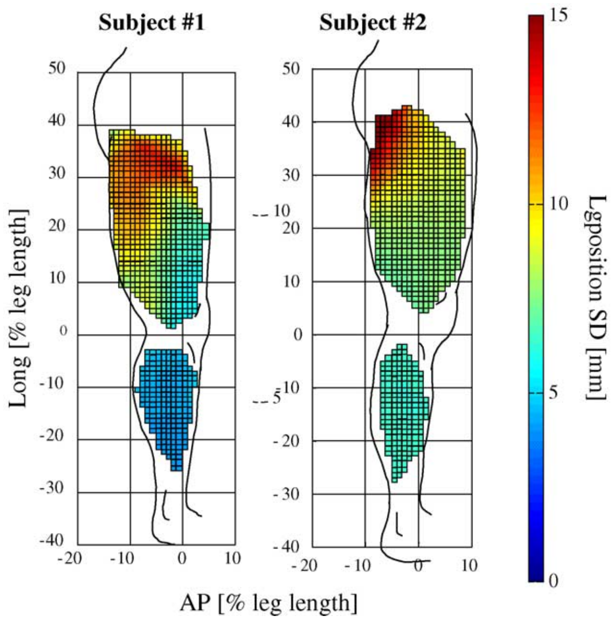

Fig. 7. Mapping of the standard deviation of the marker positions along the longitudinal anatomical direction on the thigh and shank of subject #1 and #2 during the execution of the STS motor task. Distances along the antero-posterior (AP) and longitudinal axis (Long) are expressed in percentage of the leg length of the specific subject. A sketchy depiction of the leg of the subject is superimposed.

clusters) for subject #1 and #2, respectively. Analogously, the RMS difference is up to 116.6% (EG task, ThP–ShT clusters) and 61.8% (STS task, ThP–ShT clusters) for In/Ex. According to data reported in Fig. 9, for subject #1 the lowest values of RMS difference for Fl/Ex and Ab/Ad are obtained for all motor tasks with the ThD–ShD clusters, whereas for In/Ex the lowest values are obtained with the ThP–ShT clusters for SC and SUD tasks, and with ThD–ShD cluster for STS and with ThC–ShT cluster for EG task. For subject #2, the lowest RMS difference is obtained for Fl/Ex angle with the ThD–ShD clusters for each motor task, as for subject #1. Minimal RMS difference in Ab/Ad was obtained with ThT–ShT clusters for SC, SUD and EG motor tasks, and with ThP–ShT clusters for STS. Finally, for In/Ex, the lowest RMS difference is obtained with ThD–ShT clusters for all motor tasks but STS, for which the minimum was obtained with ThT–ShT clusters (see Supplementary Table 2).

Regarding the standard deviation of the orientation of the technical reference frame evaluated for the thigh skin marker cluster in the corresponding anatomical reference frame, subject #1 shows larger changes than subject #2 for all motor tasks. The standard deviation of the orientation of the thigh technical frame ranged from 17° to 28° during SC, STS and SUD and from 9° to 11° during EG in subject #1. It ranged from 3° to 6° during all motor tasks for subject #2. Standard deviations of the orientation of the tibial cluster were all below a few degrees and were comparable for all motor tasks for the two subjects. The complete quantitative data of the standard deviation of the orientation of the technical frame for both subjects for all four motor tasks is reported in Supplementary Table 3.

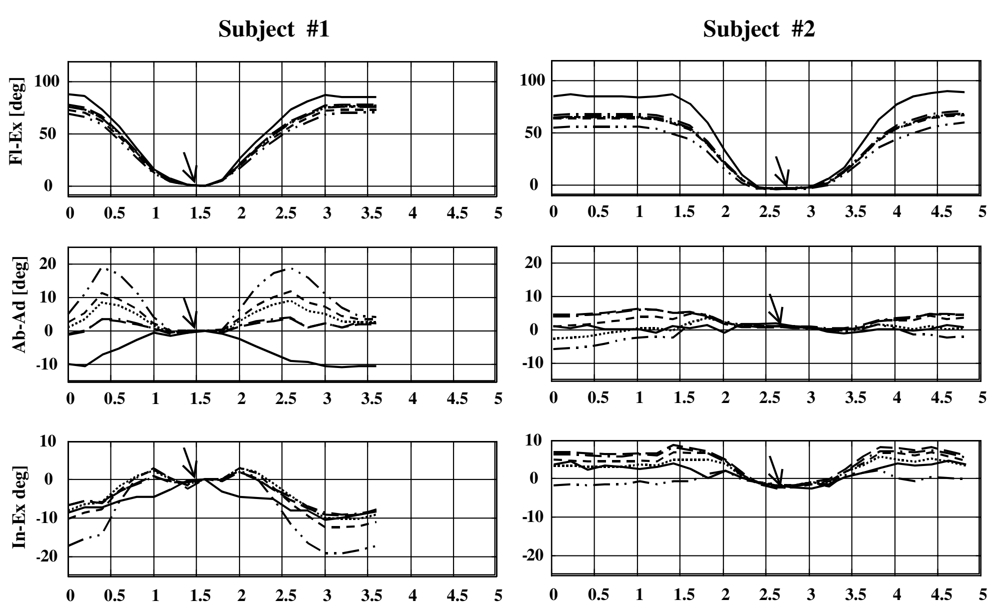

Fig. 8. Knee rotation angles calculated from the fluoroscopy-based gold standard (solid line) and from stereophotogrammetry using ThT–ShT (dotted line), ThP–ShT (dashed double-dotted line), ThC–ShT (dashed line), ThD–ShT (dashed-dotted line), and ThD–ShD (large dashed line) clusters. The STS task for subject #1 (on the left), and subject #2 (on the right) is reported. The arrow indicates the calibration reference position.

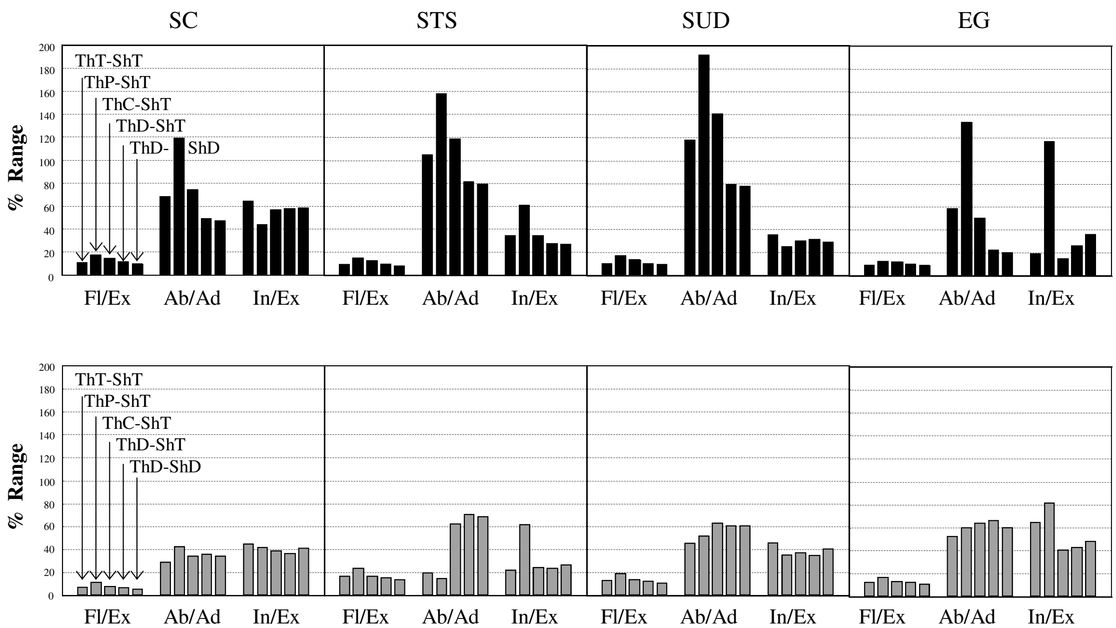

Fig. 9. Bar plot of the root mean square difference in percentage of the corresponding range of the Fl/Ex, Ab/Ad and In/Ex at the knee. These are calculated from skin markers using the clusters ThT–ShT, ThP–ShT, ThC–ShT, ThD–ShT and ThD–ShD for the thigh and shank, with respect to the gold standard calculated from 3D fluoroscopy. Data are reported for both subjects (#1 in black and #2 in grey) and for SC, SUD, STS and EG motor tasks. The numerical data are reported in Table 2 provided as on-line additional material.

4. Discussion and conclusions

STA was fully quantified for the first time in 3D and without any constraint to skin motion during the execution of activities of daily living in the whole thigh and shank. Displacement of skin markers in the corresponding anatomical frames was generally larger on the thigh than on the shank.

All shank markers exhibited almost the same amount of displacement in the three directions during the execution of different motor tasks. Only during EG motor task, the AP and ML displacements of the markers on the shank were larger than those on the thigh in both subjects. This can be explained considering that during this specific motor task the thigh is kept flexed at 45°, thus the gravitational contribution to STA is not time dependent and the inertial one is negligible, while the muscles of the shank are poorly contracted. Thus the skin markers attached on the relaxed soft tissues are particularly prone to gravity and inertia during the extension of the knee. During all the other motor tasks skin markers on the thigh exhibited a larger displacement. Moreover, they could be divided in sub-clusters showing different STA characteristics. In particular, markers on the posterior side of the thigh showed the largest ML displacement, and those on the postero-proximal area along the Long direction. This behaviour was found for both subjects in all motor tasks, and can be explained considering the characteristics of the subjects under analysis: two female subjects over 60 years old. Although they were not overweight, according to their body mass index, a thicker layer of less tonic soft tissue is present on the posterior and proximal area of the thigh, which is more prone to inertial and gravitational effects. In general, STA is both subject and task dependent.

The evaluation of STA propagation to knee rotations demonstrated that joint kinematics evaluation is strongly affected by the choice of the cluster of markers. In particular, while STA propagation to the Fl/Ex angle is limited, the measure of In/Ex and Ab/Ad in particular can be invalidated by RMS errors up to 117% and 192% of the corresponding range, respectively. The differences in the way of propagation demonstrate the subject- and task-specificity of the phenomenon, but the criticality of the propagation of STA to In/Ex and Ab/Ad is common to both subjects and all motor tasks, and can nullify the usefulness of these measurements in the interpretation of gait analysis data.

Comparison of the present results with those reported in the literature is made difficult by the different techniques used, the large variability in the subjects analysed, the different motor tasks performed and the location of the skin markers. Most of previous studies reporting quantification of STA have analysed walking and running using external fixators (Angeloni et al., 1992), or intracortical pins (Reinschmidt et al., 1997a; Westblad et al., 2000; Yack et al., 2000) or percutaneous trackers (Holden et al., 1997; Manal et al., 2000, 2002) or peculiar non-daily living motor tasks using intracortical pins (Karlsson and Lundberg, 1994; Lafortune and Lake, 1991) or Roentgen photogrammetry (Sati et al., 1996). All the studies using external fixators, intracortical pins, and percutaneous trackers reported STA up to 20 mm (Fuller et al., 1997), thus much smaller than the ones reported in the present paper. Nevertheless, STA measured using Roentgen photogrammetry (Sati et al., 1996) was up to 42 mm only in the sagittal plane for a marker placed on the distal thigh. This result supports the hypothesis of the present authors that pins or fixators strongly limit the realistic quantification of STA during daily living activities. Moreover, the motion of skin markers of these previous studies was not quantified in those positions which have been shown to be the most critical in the present study, such as the proximal-posterior area of the thigh. The hypothesised limitation to STA given by the use of pins or fixators justifies also the smaller error propagated to knee rotations reported in these studies (i.e. 10% on Fl/Ex, 20% on Ab/Ad, and 100% on In/Ex (Cappozzo et al., 1996)). Although these differences, the criticality of STA propagation to Ab/Ad and In/Ex with respect to Fl/Ex is in agreement with the results here reported. Finally, when different motor tasks were analysed (Fuller et al., 1997) the STA was assessed to be task dependent as reported in the present study.

This study points out that no precise indication can be given for careful positioning of the skin markers in order to limit STA propagation to knee rotations: considering the most critical Ab/Ad angle the cluster combination ThD–ShD seems to be to prefer for subject #1, ThT–ShT for subject #2. The small sample of analysed subjects does not allow for large generalization of the results of STA propagation to knee kinematics. Anyway, the extremely different behaviours observed even in these two subjects suggest that not even the amount of STA is a good indication of its effect on knee rotations. The amplitude of STA in subject #2 was larger than in subject #1, but its propagation to knee rotations was less critical. This can be explained observing how STA affects the orientation of the cluster with respect to the underlying bony segment: larger deformations on skin marker clusters do not necessarily correspond to larger changes in the skin-bone relative orientation. Referring to the characteristics of these two specific subjects, this behaviour can be explained by considering that subject #2 was more tonic than subject #1, thus her larger STA probably resulted more from muscle contraction than from passive effects. This is supported by the observation of the largest STA in subject #2 during SC and STS, which are probably the most demanding from the point of view of muscle contraction. The only possible general suggestion is not to position the thigh cluster in the proximal area of the thigh.

In conclusion, whereas the calculation of Fl/Ex at the knee by means of external markers can be considered acceptably reliable, this is not true for In/Ex and Ab/Ad. In order to improve the performance of stereophotogrammetric-based human motion analysis, devising validated STA compensation methods is felt necessary. This compensation method should take into account the STA characteristics of the specific subject and motor task. In this context, the data of the present study allows an in-vivo assessment of the performance of different methods for STA compensation proposed in the literature (Stagni et al., 2003). The innovative methodology developed to perform this study allows STA to be characterised more extensively on much larger samples of subjects.

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Supplementary data

Supplementary data associated with this article can be found at www.sciencedirect.com, doi:10.1016/j.clinbiomech.2004.11.012.

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