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Technical note

Assessment of reproducibility of thigh marker ranking during walking and landing tasks

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ABSTRACT

The aim of this paper is to analyse the repeatability of marker deformation and marker ranking across subjects and motor tasks. A method based on the solidification of the thigh with optimized rototranslation was applied which used 26 markers placed on the left thigh. During five trials of landing and five trials of walking for eight participants, the deformation between the actual positions of the 26 markers and the recalled positions from solidification were calculated. Markers were then sorted and ranked from the most deformed to the least deformed. Like previous studies, marker deformation found in this paper is subject and movement-dependant. The reproducibility of the marker rankings was assessed using Kendall's coefficient of concordance. Results highlighted that the marker ranking was similar between the trials of landing and between the trials of walking. Moreover, for walking and landing the rankings were consistent across the eight subjects.

1. Introduction

A fundamental assumption in human movement analysis is to consider human segments as rigid bodies in order to simplify the application of the laws of mechanics. Human segments are composed of bones and soft tissues and although in most instances the bones approximate rigid bodies, often the soft tissues do not. This can give rise to soft tissue artefacts (STA) due to muscular contractions, skin elasticity and wobbling masses [1] where STA are defined as skin movements relative to the underlying bone [2,3]. Researchers are continually trying to mitigate the influence of STA on the assessment of joint kinematics by analysing deformations of several marker sets [4–6]. Quantification of STA has been determined based on medical imaging [4,7], mathematical procedures [5,6,8–11] or by comparison with imaging or intra-cortical pins [12]. Since methods based on stereophotogrammetry found similar STA to fluoroscopy [5,6], non-invasive approaches are used more and more since they can be applied to larger populations and utilize more extensive movements without range of motion limitation [13].

Papers previously cited have proposed methods for assessing bone kinematics by reducing the STA. However, soft-tissue dynamics plays an important role, especially in joint dynamics during impacts by reducing joint loads and passively dissipating energy [14]. For example, a wobbling mass model of landing from a drop better reproduced the vertical ground reaction force than a rigid body model did and had lower joint forces and torques [1]. In gross motion analysis it can be more important to assess the kinematics of the whole segment than focus on the bone kinematics. Indeed the mass of the bone only represents 30% of the total mass of the thigh [15]. As a result soft tissue dynamics should play an important role in joint dynamics [15,16]. Given this fact marker locations that represent the best whole segment motion need to be determined in order to better estimate joint torques.

To analyse three-dimensional (3D) kinematics, local systems of coordinates (SoC) are defined from bony landmarks and joint centre locations [17] so that joint kinematics can be interpreted in anatomical terms (e.g. flexion-extension, abduction-adduction and internal-external rotation). For the thigh the greater trochanter, femoral condyles and hip joint centre are the ISB recommended landmarks [18]. Using motion analysis systems, anatomical landmarks are given by either skin mounted markers or, the Calibrated Anatomical System Technique (CAST [19]). For joint centre location, much interest has been shown in the functional approach [20,21]. For a fully defined system both CAST and functional methods require technical markers ($n \geq 3$) on each segment and locations are often chosen to minimize STA and occlusions. Only a few papers have focused on technical marker placement [4–6] even though different marker sets have been shown to result in different joint centre locations [22,23]. Indeed STA are non-homogeneous and

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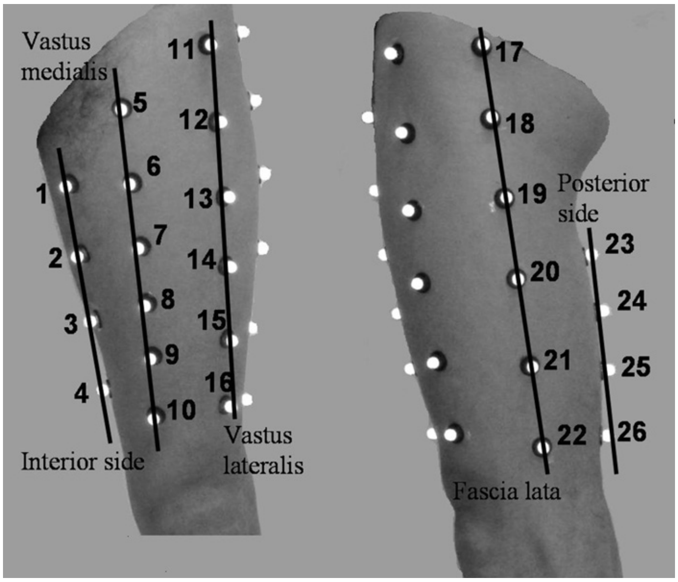

Fig. 1. Location of the 26 markers on the left thigh.

probably subject and task dependent. Our main objective is to determine marker locations on the thigh that fit the best whole kinematics of the thigh as defined by markers on the surface. Due to specific muscular contractions and body composition, the absolute magnitude of soft tissue motion is (i) subject-specific [2,4] which complicates the determination of optimal marker set for a population and (ii) task-specific [4,24]. We hypothesized that an analysis based on ranking instead of absolute deformation should provide a better insight into surface movement. Our assumptions are that the intra/inter-subject and inter-movement marker rankings are reproducible. These hypotheses were evaluated on two movements with different acceleration, namely walking and landing using a non-invasive approach on eight subjects.

2. Methods

In the present study, the algorithm of Monnet et al. [25] (presented below) and recommendations of Roosen et al. [22] were applied to define the thigh as a rigid segment based upon a static configuration. Marker deformation was calculated as the Euclidean distance between the recorded marker location and its recalled location from a rigid segment assumption. The deformation was analysed in terms of absolute value and also by ranking to avoid subject-specific soft tissue range of motion confounding results across subjects.

2.1. Equipment set up

Eight male participants (23.0 ± 2.9 years old, 178 ± 3.7 cm, 73.6 ± 5.6 kg, body fat percentage 12.2 ± 3.6) took part in this study after giving informed consent in accordance with local ethical procedures. Movement data were collected at 300 Hz using a 10 camera Vicon system (T40, 4 Mpx). No signal processing was applied to the raw data. A set of 26 markers (⌀14 mm) was methodically placed on the left thigh with double-sided tape (Fig. 1). They described five vertical lines of four to six equidistant markers: interior side of the thigh, vastus medialis, vastus lateralis, fascia lata and posterior side of the thigh. This placement was reproducible across subjects [26] and covered all the thigh parts that could be seen during the movements and gave a representation of the overall segment kinematics.

2.2. Static acquisition

A reference geometry for the set of markers was acquired for all subjects during a 3 s static anatomical posture. From this posture the local coordinates ${}^{L}\boldsymbol{m}_i$ of each marker (i = 1–26) were calculated from its global coordinates ${}^{G}\boldsymbol{m}_i$. The local frame $\mathcal{R}_L$ was created using all the markers [24]. The origin $G_{\boldsymbol{t}}$ of the local frame was determined as the centroid of the 26 markers and ${}^{G}R_L$ is the rotation matrix from global to local frame:

$$ {}^{L}\boldsymbol{m}_i = {}^{G}R_L({}^{G}\boldsymbol{m}_i - {}^{G}\boldsymbol{t}) \quad (1) $$

with

$$ {}^{L}\boldsymbol{m}_i = \begin{bmatrix} {}^{m}x_i \\ {}^{m}y_i \\ {}^{m}z_i \end{bmatrix}_{\mathcal{R}_L} \quad {}^{G}\boldsymbol{m}_i \begin{bmatrix} {}^{m}x_i \\ {}^{m}y_i \\ {}^{m}z_i \end{bmatrix}_{\mathcal{R}_G} \quad \text{and} \quad G_{\boldsymbol{t}} = \frac{1}{n}\sum_{i=1}^{n} {}^{G}\boldsymbol{m}_i \quad (2) $$

The rotation matrix was calculated in each time frame using the optimization procedure described in Bouby et al. [27] that involves all the markers (see Appendix A). Average local coordinates calculated over the duration of the static acquisition were used as the reference position in the following sections.

2.3. Walking and landing trials

Subjects were asked to perform five walking trials at a self-selected speed of progression and five landing trials from a height of 0.7 m. After marker reconstruction, a successful trial was determined as one with marker occlusions in less than 1% of frames. During each trial, the recalled positions (${}^{G}\boldsymbol{r}_i$) of the markers were calculated in the global frame using their local coordinates (${}^{L}\boldsymbol{m}_i$), previously determined during static acquisition, and the optimized rototranslation (${}^{L}R_G$; $G_{\boldsymbol{t}}$):

$$ {}^{G}\boldsymbol{r}_i = {}^{L}R_G {}^{L}\boldsymbol{m}_i + G_{\boldsymbol{t}}. \quad (3) $$

Then for each marker i the Euclidean distance between its *actual* positions (${}^{G}\boldsymbol{m}_i$) and its *recalled* positions (${}^{G}\boldsymbol{r}_i$) was calculated at each instant of time:

$$ d_i = \sqrt{({}^{m}x_i - {}^{r}x_i)^2 + ({}^{m}y_i - {}^{r}y_i)^2 + ({}^{m}z_i - {}^{r}z_i)^2}, \text{ with :} \quad (4) $$

$$ {}^{G}\boldsymbol{r}_i = \begin{bmatrix} {}^{r}x_i \\ {}^{r}y_i \\ {}^{r}z_i \end{bmatrix}_{\mathcal{R}_G} \quad (5) $$

The deformation associated with each marker was defined as the average distance ($\bar{d}$) over all frame numbers of a trial. The deformation calculated in this paper does not correspond to STA as the reference was the global segment kinematics based on all the markers and not the bone kinematics. Finally ranking procedure was performed: the first rank was accorded to the least deformed marker while the most deformed was ranked at the 26th position.

2.4. Statistical analysis

A mean deformation was calculated over the five trials of each movement. Results were tested for normality with the Shapiro-Wilkinson test. Then, a three ways (movement, subject, markers) repeated measures ANOVA was used to test for significant difference (α < 0.01) among the marker deformations, the subjects and the movement.

Kendall's coefficient of concordance (W [28]) was then calculated to assess the agreement of the marker ranking between the five trials of walking and between the five trials of landing for each