ANALYSIS OF SKELETAL MOTION KINEMATICS FOR A KNEE MOVEMENT CYCLE

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This study estimated the skeletal motion for a knee motion cycle. The surface markers on the thigh and the shank showed the computed displacement during in vivo motion analysis. This error was minimized using optimization procedure. The displacement was generally greater on the thigh than the shank. The minimization of error produced by this procedure was more successful on the thigh than the shank. The purpose of this study was to require high value motion data. These results provide the basis to calculate the instantaneous knee axis of rotation in a follow up study

Keywords: skeletal motion, motion analysis, surface markers, instantaneous knee axis of rotation, optimization procedure

INTRODUCTION

Magnetic Resonance Imaging (MRI) and fluoroscopy are more precise methods in comparison to motion analysis using surface markers, regarding accuracy of measurement. In recent years motion analysis has been of particular interest for investigators performing inverse kinematics. Different methods were developed to quantify the relative motion of body segments. Recent studies investigated the motion of body segments using surface markers. Corresponding motion data were transformed into skeletal motion using principles of analytic geometry (Cappozzo, Cappello and Pensalfini 1997, Cappello et. al. 1997). The analysis of body segments during motion can be done using several methods: One method is avoiding error and the other method is to minimize the error. Investigators considered inaccuracies of motion capture systems and skin displacement which produced erroneous motion data (Fisk 2004). LaFortune et. al. (1992) and Taylor et. al. (2005) eliminated errors using bone pins. However, the post operation motion data changed the walking pattern due to surgical operation and medication. Lundberg et. al. (1989) implanted x-ray-impermeable markers on the bone. This method reduces the surgical intervention. However, the subject is exposed to increasing radiation during measurements. The motion data resulting from bone pins and x-ray-impermeable markers are more accurate than those produced by surface markers. Therefore the bone position of the markers could be reconstructed nearly in a ratio of 1:1 during motion. But the computed displacement of surface markers can be minimized using optimization procedures (Andriacchi et. al. 1998). Afterwards, the resulting motion data given by markers on the skin are comparable to data of the markers at the bone position. Relative marker skin positions shaped the geometry of the marker cluster on the skin surface which described location and moving direction of spatial body segment motions (Cappello et al. 1997, Fisk 2004). In this context the task of this study is to estimate the skeletal motion kinematics of *femur* and *tibia* for a knee motion cycle.

METHODS

Right leg kinematics of the subject was measured during motion analysis. The right knee was free of pain, trauma and able to work under load as well as to perform full range of motion (ROM). 44 markers on the right thigh and 37 markers on the right shank were placed all around the leg. Markers were located collinear and in a distance of 2 cm from each other. Six vicon cameras (240Hz) captured the object in a distance of 3 to 4 m with a resolution of 0.3 mega pixel. At the beginning of the test procedure the subject was holding the right leg at an angle of 90° at the hip and 140° at the knee, standing on the left leg on a platform (20 cm over the ground). While performing knee motion cycles, the subject was holding the right foot in a dorsal extended position. Afterwards kinematic analysis and calculation of skeletal motion were performed for a full extension flexion motion in the knee joint (knee motion cycle) and analysed with MATLAB™. For estimating the thigh and the shank position, the definition of local coordinate systems was required (Andriacchi et. al. 1998). The product of the transposed rotation matrix and the local coordinate system equals local coordinates (equation 1).

$$\mathrm{L}(t)_i = R^T(t) \cdot (\mathrm{G}(t)_i - \mathrm{C}(t)) \quad i = 1 \ldots n \qquad (1)$$

The computed displacement leads to differences between time histories of local coordinates of the marker cluster and reference coordinates. The differences can be minimized by optimizing ($\boldsymbol{m}(\boldsymbol{\varepsilon}(\boldsymbol{t_s})_i)$) (equation 2a, 2b).

$$\mathrm{m}(\varepsilon(t_s))_i = 1 - \varepsilon(t_s)_i \cdot \left(\frac{\Delta \mathrm{L}(t_s)_i}{\max(\Delta L((t_s))_i)} \right) \quad \text{for } \varepsilon \geq 0 \qquad (2a)$$

$$\mathrm{m}(\varepsilon(t_s))_i = 1 - \varepsilon(t_s)_i \cdot \left(2 - \frac{\Delta \mathrm{L}(t_s)_i}{\max(\Delta L((t_s))_i)} \right) \quad \text{for } \varepsilon < 0 \qquad (2b)$$

The optimization procedure (to Levenberg – Marquardt) finds a parameter $\varepsilon(t)_i$ on the position of local minimum at function $\mathrm{F}(\mathrm{m}(t_s))_i = |\lambda(t_s) - \lambda(t_0)|$ (minimizing of eigenvalue distance squares – Marquardt 1963). $\varepsilon(t)_i$ has the task to produce an optimal ($m(\varepsilon(t_s)_i)$). Equation (2) assigns the lowest mass to the greatest displacement and vice versa.

RESULTS AND DISCUSSION

The calculated displacement is comparable to the total measurement error which is shown in this part. During which markers (white) 28, 32 and 33 were moving a maximum of 4.7 cm on the lateral skin surface of the thigh and 7.2 cm on the shank (Figure 1, right). Markers (hatched) 24 up to 27 and 29 up to 31 were moving a maximum of 1.7 cm on the thigh and markers 28 up to 30 as well as 32 up to 33 0.3 cm on the shank. On the ventral skin surface the thigh markers (black) 34 and 35 were moving a maximum of 5.3 cm (34) and 4.5 cm (35) as well as markers (black) 10 and 11, 5.4 cm (10) and 5.9 cm (11) on the shank (Figure 1, left). Markers 36 up to 44 were changing by a maximum of 1.2 cm on the thigh and markers 12 up to 18 by 0.45 cm on the shank, regarding the rigid body movement (Figure 1, left). On the dorsal skin surface of the thigh and the shank the maximum measured displacement was 6.0 cm and 7.5 cm. The medial surface markers were moving a maximum of 5.8 cm on the thigh and 6.6 cm on the shank. The optimization procedure caused a greater effect on markers of the thigh than of the shank. This means that the procedure minimized the errors on the thigh better than the shank. The amount of minimizing was maximum 0.5 cm to the lateral surface markers on the thigh and 0.1 cm, respectively ventral (Figure 2A, Figure 2B). In spite of the positive effects on the thigh, derivation for rigid body behaviour was less on the shank. From the results of this study the following aspects were deduced: A marker with greater measurement error influenced the measurement error of all other markers and the centre of mass within the marker cluster negatively. The measured displacement also comprehends inaccurate measurements of the motion capture system. For example of a knee model with rigid body segments, Fisk (2004) evaluated the measurement accuracy of motion capture systems. The author used the knee kinematics as parameters for the measurement accuracy. Considering the results of this study a measurement error of 2 mm (during translation) and 0.5° (during rotation) has to be accepted using the VICON system. A multiplier of measurement accuracy is the distance between the cameras and the measurement field as well as the marker size. In the following the other causes of the computed displacement will be discussed: The skin in the dorsal area is soft and shows higher flexibility. The underlying *fascia* has no connective tissue septes, which connect the superficial *fascia* with the bone.

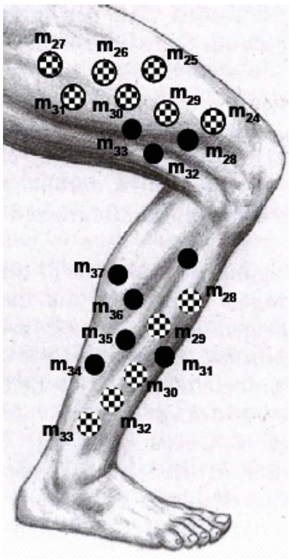

Figure 1: Right: The right leg in the sagittal plane – lateral – with markers 24 up to 33 on the thigh and markers 27 up to 37 on the shank. Left: the right leg in the frontal plane – ventral – with markers 34 up to 44 on the thigh and 10 up to 18 on the shank

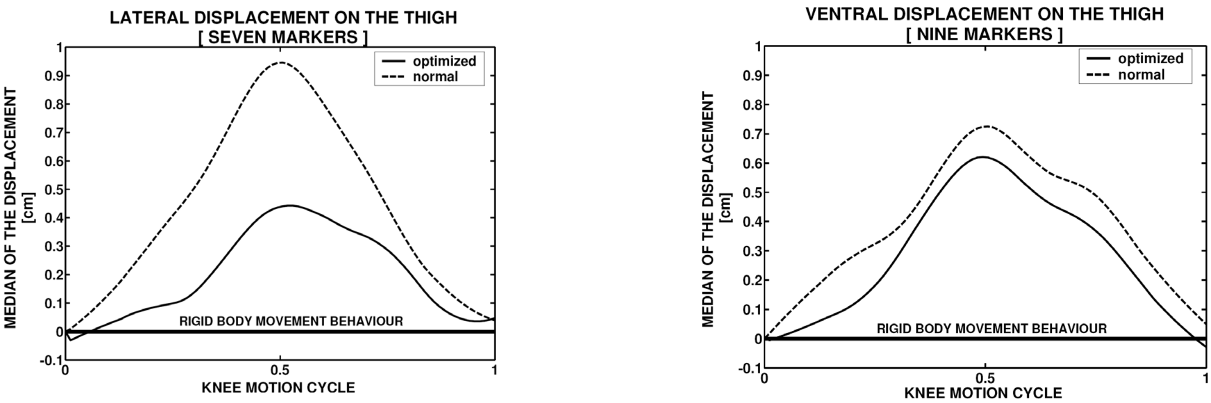

Figure 2: A) Median courses before (--) and after (-) the optimization procedure of displacement (hatched markers of lateral skin area on the thigh) during a knee motion cycle. B) Median courses before (--) and after (-) the optimization procedure of displacement (hatched markers of ventral skin area on the thigh) during a knee motion cycle.

Therefore, this skin area is thinner and more elastic. It has to provide mobility and thrust bearing capability for the musculature. Medial located markers were attached to soft and loose skin. The skin thickness of the thigh decreases in proximal direction. During knee flexion this skin area at the thigh is the basis for the free adductor channel and allows a free movement for the m. gastrocnemius at the shank. Markers 36 up to 44 showed smaller displacements on the thigh than the markers 34 and 35. The skin on the ventral leg side is exposed to greater environmental stimuli than the dorsal and the medial leg side. On this account this skin area is also thicker than the skin of the medial and the dorsal leg side. The fascia lata surrounds muscles of the thigh completely. This fascia increases in lateral direction. The skin stiffness is compounded by septum inter muscular medial and lateral which connects to the femur. The skin covered by markers 12 up to 18 on the shank is less flexible. It’s dry and solid as well as often sticks to the periosteum. The skin stiffness in this area is also compounded by fixing positions of the fascia (margo anterior and medial) on the tibia. Markers 24 up to 27 and 29 up to 31 moved less than markers 28, 32 and 33 on the thigh. Generally these markers were located on the tractus iliotibialis, which prescinds the fascia lata. The tractus iliotibialis requires big surface on the lateral side of the thigh. This fibre bundle retards the skin flexibility by its tensions and muscular connections (m. gluteus maximus, m. tensor fasciae latae and m. gluteus medius). The lower dermis can also stick to the tractus iliotibialis. Therefore this special bundle permits little skin displacement during motion. Markers 30, 32 and 33 on the shank are located over two connective tissues which connects the surface fascia to the fibula. This condition limitates the skin movement significantly. The retinaculum and the mm. extensorum superius do not require little skin mobility on this area during activity. As a result markers 30, 32 and 33 show less skin displacement than markers 27, 31 and 34 up to 37.

CONCLUSION

It is recommended to place markers on the lateral and the ventral skin surface of the thigh and the shank in vivo motion analysis. Attributes of the skin and the activities of the underlying connective tissues are associated with magnitude of the calculated displacement during movement. This displacement was minimized using optimization procedures. According to this motion the data quality was improved to provide a basis for further data analysis. In a follow up study relative velocities of the *femur* and the *tibia* in a two dimensional knee model (according to Menschik 1987) were calculated. These results will be used to calculate the instantaneous pole for the knee joint.

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