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Quantification of the segmental kinematics of spontaneous infant movements

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ABSTRACT

This article introduces a method to capture the movements of the upper and the lower limb of infants using an electromagnetic tracking system and to reliably calculate the segmental kinematics. Analysis of the spontaneous movements of infants is important e.g. in the context of the "General Movement Analysis", which aims at the early diagnosis of motor dysfunctions. Due to special constraints regarding infant anatomy, previous approaches based on optical tracking could only gather position data of the infant' segments, whereas with this method in addition relative segment angles can be calculated. The spontaneous movements of the infant and simple calibration movements of the hand and the foot are used to calculate the joint centers and the joint axes of a multi-segmental chain model. The quality of the calibration movements is assessed at calibration time by calculating the root mean square deviation from the total least squares regression plane. The general accuracy of the recording is evaluated by the difference between recorded and estimated sensor positions and the difference between recorded and estimated sensor orientations. Movements of 20 infants between term and 3 months post term age were recorded and processed. A first application illustrates how abnormal movement patterns are manifested in the segmental kinematics. The results show that the presented method is a practicable and reliable way to record spontaneous infant movements and to calculate the segmental kinematics.

1. Introduction

In infancy and early childhood, mental, behavioral and motor dysfunctions result in abnormal movement patterns (Teitelbaum et al., 1998; Frisone et al., 2002; Zafeiriou, 2004; Gosselin et al., 2005). Hence, motor pattern analysis is the hallmark of neurological evaluation at that age group. This analysis is usually conducted on the basis of video recordings. The evaluation of such recordings is of a subjective nature and often demands much effort for training and analysis (Valentin et al., 2005). An objective analysis by the means of three-dimensional (3D) motion capturing could give valuable decision support for physicians. Therefore, a method to collect and derive reliable and reproducible parameters describing the spontaneous movements of the infant is needed. This paper introduces an approach which is well suited for this purpose.

Movement analysis has gained widespread use in medical applications. The position and the orientation of the body segments are used to describe the movement of the body in a repeatable and quantitative way. Since these parameters cannot be measured directly, markers or sensors are attached to the skin. To render reliable measurements, a relation between the coordinate systems (CSs) of the sensors and the morphology has to be established. The common way to associate a CS with a segment is to define the axes and joint centers relative to specific anatomical landmarks (Wu et al., 2002, 2005). Some joint positions and axes can be calculated using special calibration movements (Piazza et al., 2001; Ehrig et al., 2007). The application of 3D movement analysis to infants imposes constraints to these methods:

1. Infants do not yet possess palpable landmarks.
2. The segments of infants are small.
3. It is not possible to execute complex and time-consuming calibration movements.

These constraints demand a new method for the reproducible movement analysis of infants. Meinecke et al. (2006) report on motion capture of infants using an optical tracking system. Due to the second limitation they could only attach one marker per limb

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segment. Thus this approach was restricted to collecting positional data for the limbs. The main contribution of this article is to introduce a novel method to calculate the segmental kinematics of infant movements. The method uses the spontaneous movements of the infant and thus it needs only ad hoc movements. An evaluation shows that the method is reliable and practicable. Furthermore we show in a first example of use that abnormal movement patterns are manifested in the derived movement parameters.

2. Methods

2.1. Experimental protocol

The motions of the infants were recorded with an electromagnetic (EM) tracking system (3D Guidance^{TM}, Ascension Technology Inc.) with a sample frequency of 50 Hz. Four sensors (see Fig. 1) are attached to the upper limb and four to the lower limb of one side of the body. At the upper limb one sensor each is attached to the dorsal side of the hand, the distal dorsal forearm, the distal dorsolateral upper arm and the dorsal shoulder just above the scapula. At the lower limb one sensor each is attached to the dorsal side of the foot, the distal side of the shank, the distal dorsolateral thigh and to the superior anterior iliac spine of the pelvis. Four minor calibration measurements are necessary to calibrate the model which will be referred to in the following sections as movements A, B, C and D. First a physiotherapist rotates the hand of the infant around the flexion axis (A). Then she tries to align the hand so that the wrist is straight (B), i.e. the flexion/extension angle and the abduction/adduction angle are 0. The lower limb is calibrated in the same manner: the foot gets rotated over the flexion axis (C) and the foot is aligned (D). For the flexion/extension movements A and C the physiotherapist tries to avoid any abduction/adduction. Subsequently the infant can move arbitrarily on its back (see Fig. 2). The movements are recorded 5 min each for the upper and the lower limb, since due to current restrictions of the tracking system it is only possible to track four sensors synchronously.

This study was approved by the Ethics Committee of the University of Heidelberg. Before the study, the experimental protocol was explained to all parents and their written informed consent was obtained.

2.2. Model definition

The rigid body model consists of three segments each for the upper and the lower limb. Each segment is represented by a Cartesian CS, the so-called segment coordinate system (SCS). Every SCS is represented by a homogeneous transformation matrix T (see Fig. 2). For the sake of simplicity we assume nominal axes, i.e. fixed, orthogonal axes (Wu et al., 2002; Cappozzo et al., 2005). For two adjacent segments the relative rotation matrix R between the SCSs establishes a joint coordinate system (Grood and Suntay, 1983). Thus Cardanic angles with an anatomical meaning can be calculated for the rotation matrices R_W of the wrist joint, R_E of the elbow joint, R_K of the knee joint and R_A of the ankle joint. It should be noted that no hip and shoulder angles can be calculated with this model. The current arm pose is defined by the parameters

$$\{T_{UA}(t), l_{UA}, R_E(t), l_{FA}, R_W(t)\} \tag{1}$$

where $T_{UA}(t)$ is the transformation matrix of the upper arm, l_{UA} is the length of the upper arm and l_{FA} is the length of the forearm. The current leg pose is defined by the parameters

$$\{T_T(t), l_T, R_K(t), l_S, R_A(t)\} \tag{2}$$

where $T_T(t)$ is the transformation matrix of the thigh, l_T is the length of the thigh and l_{SH} is the length of the shank. For all SCSs the direction of the axes are defined in the same manner: The x-axis corresponds to the longitudinal segment axis in proximal direction. The y-axis corresponds to the flexion axis in lateral direction. The z-axis is perpendicular to the x- and the y-axis.

In the following sections the SCSs will be specified for each segment. One sensor with 6 degrees of freedom (DOF) is attached to each segment. The CSs of the sensors, the so-called technical frames, are represented by transformation matrices. To associate each SCS with the technical frame of the corresponding sensor, the orientation of the joint axes and the position of the joint centers have to be defined relative to the technical frame. Fig. 2 shows the joint positions p_{s1} of the shoulder, p_{e2}, p_{e1} of the elbow, p_{w2}, p_{w1} of the wrist, p_{h1} of the hip, p_{k2}, p_{k1} of the knee and p_{a2}, p_{a1} of the ankle.

2.3. Calculation of joint centers

To determine the average center of rotation of two adjacent segments, the relative position ${}^{S1}p_1$ in the first technical frame and ${}^{S2}p_2$ in the second technical frame have to be calculated. This is done by minimizing the distance between their global positions ${}^{G}p_1$ and ${}^{G}p_2$:

$$\Delta p = \frac{1}{T}\int_0^T ({}^{G}p_1(t) - {}^{G}p_2(t))^2 \mathrm{d}t \tag{3}$$

We use all spontaneous movements of the infant to minimize the integral in place of passive calibration movements as used in the approach of Biryukova et al. (2000). During the recording the adjacent technical frames assume a multitude of different orientations toward each other. The evaluation will show that this information suffices to reliably determine the rotation centers. By exploiting these data no calibration movements have to be executed.

2.4. Definition of segment coordinate systems of the upper limb

2.4.1. Forearm

The axis ${}^{S2}y$ of flexion/extension in the wrist is determined functionally using calibration movement A, where the physiotherapist moves the hand over this axis trying to avoid any abduction/adduction. Frigo et al. (1998) used a similar approach to correct the orientation of the knee flexion axis. During this movement the hand sensor should move perpendicular to the flexion axis. The flexion axis ${}^{S2}y$ is assumed to lie in the plane E_1 that is orthogonal to the x-axis. Therefore the position data of the hand sensor is projected onto E_1. In the ideal case of a pure flexion movement the elements of this set of points p_{proj} lie on a line. A total least squares (TLS) regression line is calculated to estimate this line (see Fig. 3). The normal vector u of this line can be found by solving the optimization problem

$$\min_u \|Mu\|^2, \ \|u\| = 1 \tag{4}$$

where M is a matrix that contains the standardized elements of p_{proj} in its rows. The optimal value for u can be determined with a singular value decomposition (Nievergelt, 1994). The flexion axis ${}^{S2}y$ lies perpendicular to this line in E_1.

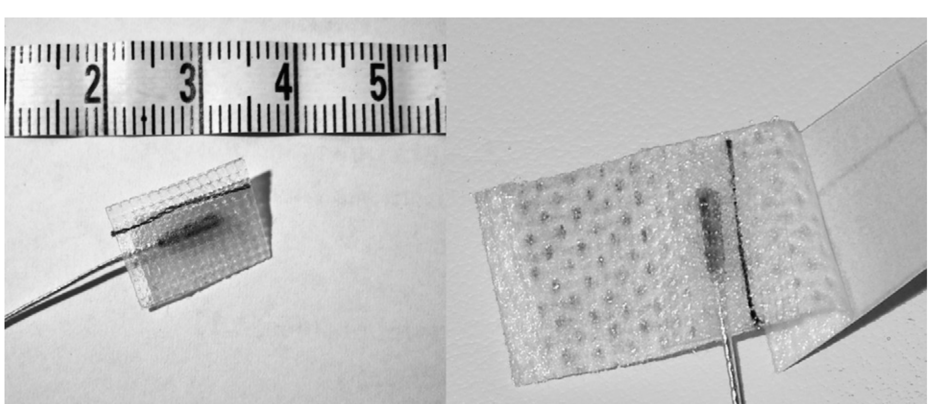

Fig. 1. Left side: Sensor of the electromagnetic (EM) tracking system (1.3 mm diameter). The sensor is embedded in a "sandwich construction" between two pieces of transparent tape. Right side: The sensor is attached to the infant skin with an eudermic patch. Thanks to the larger area of the sandwich construction the sensor does not move between the eudermic patch and the skin.