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Short communication

Design and validation of surface-marker clusters for the quantification of joint rotations in general movements in early infancy

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ABSTRACT

Lack of complexity in general movements in early infancy is an important marker of potential motor disorders of neurological origin, such as cerebral palsy. Quantitative approaches to characterising this complexity are hampered by experimental difficulties in recording from infants in their first few months of life. The aim of this study was to design and validate bespoke surface-marker clusters to facilitate data acquisition and enable full quantification of joint rotations. The clusters were validated by recording the controlled movements of a soft-body dummy doll simultaneously with an optical (Qualisys) and inertial (XSens) motion capture system. The angles estimated from the optical system were compared with those measured by the inertial system. We demonstrate that the surface-marker based approach compares well with the use of an inertial system to obtain "direct" readings of the rotations whilst alleviating the issues associated with the use of an optical motion capture system. We briefly report use of this technique in 1–5 month old infants. By enabling full quantification of joint rotation, use of the custom made markers could pave the way for early diagnosis of movement disorders.

1. Introduction

Infants born very early (less than 32 weeks post-conception) are at risk for motor delay. The Prechtl assessment of general movements, i.e., spontaneous whole-body movements present from early fetal life (Einspieler and Prechtl, 2005) has been shown to robustly predict developmental motor disorders, in particular, cerebral palsy (CP), and is usable under the age of 4 months. Being largely qualitative, this assessment has limitations in that it is difficult to measure change and assess the outcome of an intervention. Attempts to quantify the assessment using 3D motion capture (e.g., Fetters et al., 2004; Jeng et al., 2002) have often used a simplified kinematic model, and only characterized angular motion in flexion/extension. However, it is the rotations along the axis of the limbs and slight changes in the direction of movements that give the impression of complexity and variability of typical general movements (Einspieler and Prechtl, 2005). These rotations refer to "small rotatory components that are superimposed on flexions and extensions of the limbs" (Ferrari et al., 1990). The lack of quantitative data on such rotations is mostly due to experimental limitations, in particular, the lack of palpable anatomical landmarks, the large amount of soft tissue artefact, and the small size of the joints all of which make it difficult to extract the number of markers necessary for a full kinematic analysis. In addition the significant amount of time needed to apply the required number of markers makes it difficult for the infants to be tolerant of the procedure.

Alternative recording technologies have been considered that do not rely on optical tracking. For example, use of inertial sensors or electromagnetic tracking devices (EMT) has been proposed (Saber-Sheikh et al., 2010; Karch et al., 2008). Although performance in the laboratory has been shown to be good (Saber-Sheikh et al., 2010), both methods have their problems. In particular the performance of EMT degrades strongly in the presence of magnetic interferences, such as the presence of other recording devices, e.g., EMG/EEG, or metal objects (Hummel et al., 2006, Engels et al., 2010), which are routinely used in the clinical environment. The use of inertial sensors also presents a challenge as these are known to suffer from drifts in long recording sessions (Luinge and Veltink, 2005). Optical tracking methods are not subject to these drawbacks; however, their main limitation in movement capture in early infancy is that of being able to track a sufficient number of markers to achieve robust rigid body pose estimation. In particular, experimental constraints include the space available for marker placement and the set up time required for their application. The use of double sided tape to apply the markers can also contribute to the infants' distress when these are removed in large quantities.

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Here, we describe a novel approach to record spontaneous infant movement and measure all rotational elements, which is based on the use of bespoke, flexible surface-marker clusters.

2. Material and methods

2.1. Marker holder and cluster design

A computer-controlled laser cutter was used to cut cluster frames from thin (1 mm) polycarbonate sheet (Ensinger, UK). This material was chosen because it is virtually unbreakable (certainly not in the range of operation considered here) and will undergo plastic deformation rather than shatter (tensile strength 62 MPa, flexure strength 103 MPa). It is therefore safe for use with infants. As per the recommendations of Capozzo et al. (1997), the clusters (see Fig. 1, top panel) were shaped so that their longest principal axis is orientated toward the relevant anatomical landmark position (see Fig. 1, bottom panel). 21 mm wide slit holes were produced so that 20 mm wide Velcro bands can be used for fixation. The clusters were holed along the main axis to maximize flexibility across that axis, thus making it possible to bend the cluster and closely fit the profile of the limb. This approach limits slippages during movement or contact that may result in shifting of the cluster (a problem discussed in Karch et al., 2010 in the context of EMTs). A smooth fabric (in this case black felt) was placed between the skin and Velcro to avoid skin irritation. A three-marker cluster was designed for use on the shanks because in very young infants there is insufficient space for 4 markers. Holders for 7 mm (diameter) retro-reflective markers were constructed from 10 mm diameter disks cut in 3 mm polycarbonate sheet (Ensinger, UK) that were drilled into to host the bottom half of the retro-reflective markers. The holders were welded to the cluster using a solvent adhesive (methylene chloride), and the markers were glued to them using epoxy.

2.2. Validation study

A Qualisys Motion capture system (Qualisys, Sweden) was used to record controlled movements on a soft-body dummy doll and the data compared to that obtained using two other methods: (i) optical tracking of markers placed on ‘anatomical’ landmarks and (ii) motion capture using inertial sensors (XSens, Germany). A 4-marker cluster was used on the thigh. Four further tracking markers were placed on the torso of the doll. Five markers were placed on ‘anatomical landmarks’ of the doll: 2 on the knee (corresponding to the medial and lateral condyles), 1 on the hip (corresponding to the head of the femur), 2 on the shoulders (corresponding to the humeral head). Two inertial sensors were placed on hip and torso. Their axes were aligned before recordings and we verified that the sensors did not show any drift. Recordings were performed in an environment free from magnetic interferences. The doll had some articulatory capacity, therefore a series of random controlled rotations were performed around three ‘virtual’ axes, which approximately corresponded to flexion/extension, abduction/adduction, and lateral/medial rotation of the hip, with the hip and knee flexed to 90°. Data for each of the three methods were collected simultaneously. For optical tracking-based methods, rotational elements were extracted using the joint parameter estimation method of Schwartz and Rozumalski (2005).

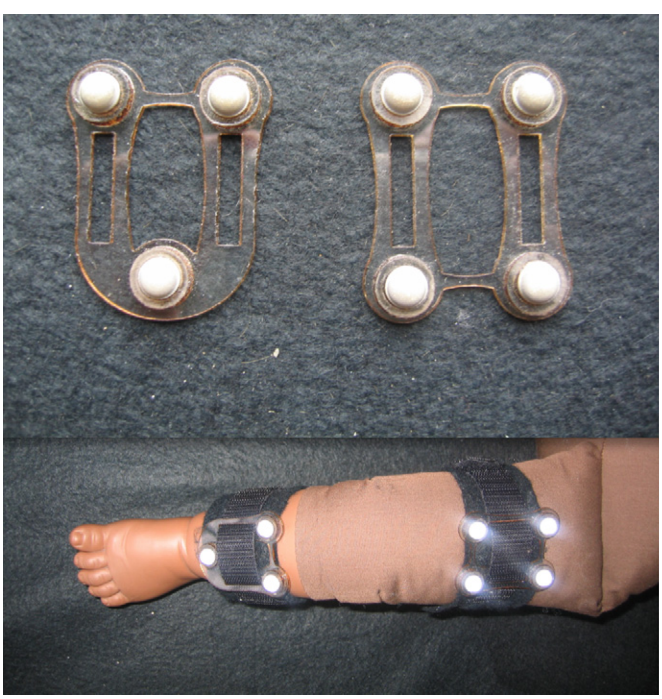

Fig. 1. Marker clusters. Top: 3-marker and 4-marker configurations. Bottom: The markers are attached to the body using Velcro bands over a layer of soft material. The flexibility of the 1 mm polycarbonate structure makes it possible to maximize contact surface and avoid slippages during movement.

2.3. Case study: data acquisition in healthy infants

With local ethical approval, a Qualisys Motion capture system (Qualisys, Sweden) was used to record spontaneous activity of 4 typically developing infants (1–5 months). A total of 37 reflective markers were applied to the trunk (4 on approximate anatomical landmarks, 9 for tracking) and the lower limbs (10 on approximate anatomical landmarks, 14 for tracking). The markers placed on anatomical landmarks were only used during a static calibration phase for model reconstruction and were removed before recording. The tracking markers were attached to the leg as per Fig. 1 (lower panel), i.e., a 4-marker cluster on each thigh and a 3-marker cluster on each shank. The average setup time for each infant was between 5 and 10 min, with two experimenters placing the markers on the baby whilst being held by its mother. The infant was then placed in supine, and spontaneous kicking movements recorded for more than 2 min (infant in Brazelton State 4: awake not crying; Brazelton and Nugent, 1995). Rotational elements were extracted as described above.

3. Results

3.1. Validation study

There was good agreement between the angular estimates produced by all three methods during flexion/extension of the leg around the hip joint (Fig. 2A). Angular differences between the proposed method and the inertial sensor based method displayed an asymmetric distribution (Fig. 2B) that can be explained by an overshoot of the inertial sensor based method on ground contact, followed by a recovery period. This recovery period can take up to 2 s and is well approximated by a 3rd order polynomial (Fig. 3). When comparing the angular estimates obtained using the proposed method with those obtained using the inertial sensor based method over 30 s of controlled movements in adduction/abduction of the dummy's leg around the hip joint (Fig. 2D), the largest range of difference was found in the lateral/medial component, the longitudinal axis being most susceptible to slippage of the inertial sensor as it is housed in a large rigid casing ($38 \times 53 \times 21$ mm^3). Finally, when rotations around all axes were considered, good agreement between methods was observed (see Table 1), with statistics consistent with those published by Saber-Sheikh et al. (2010) who compared the XSens inertial sensor with an EMT system such as that used by Karch et al. (2010).

3.2. Case study: data acquisition in healthy infants

The use of clusters significantly reduced the set up time for each infant and improved comfort as fewer markers needed to be in direct contact with the skin. Whilst the embedding of the marker within the marker holder meant that less marker surface was visible to the cameras, we found that this also meant reduced susceptibility to the loss of markers through accidental contacts occurring during the infant's movement. For example, contact of the arm with the leg, or leg to leg contact can easily displace a marker from the double-sided tape which attaches it to the body part. With a 6-camera setup, we did not observe any notable loss of visibility. Following data reconstruction, we were able to extract ranges of angular motion for hip and knee rotations as well as for the rotation angle around the equivalent rotation axis (the axis defined by the eigenvector corresponding to the

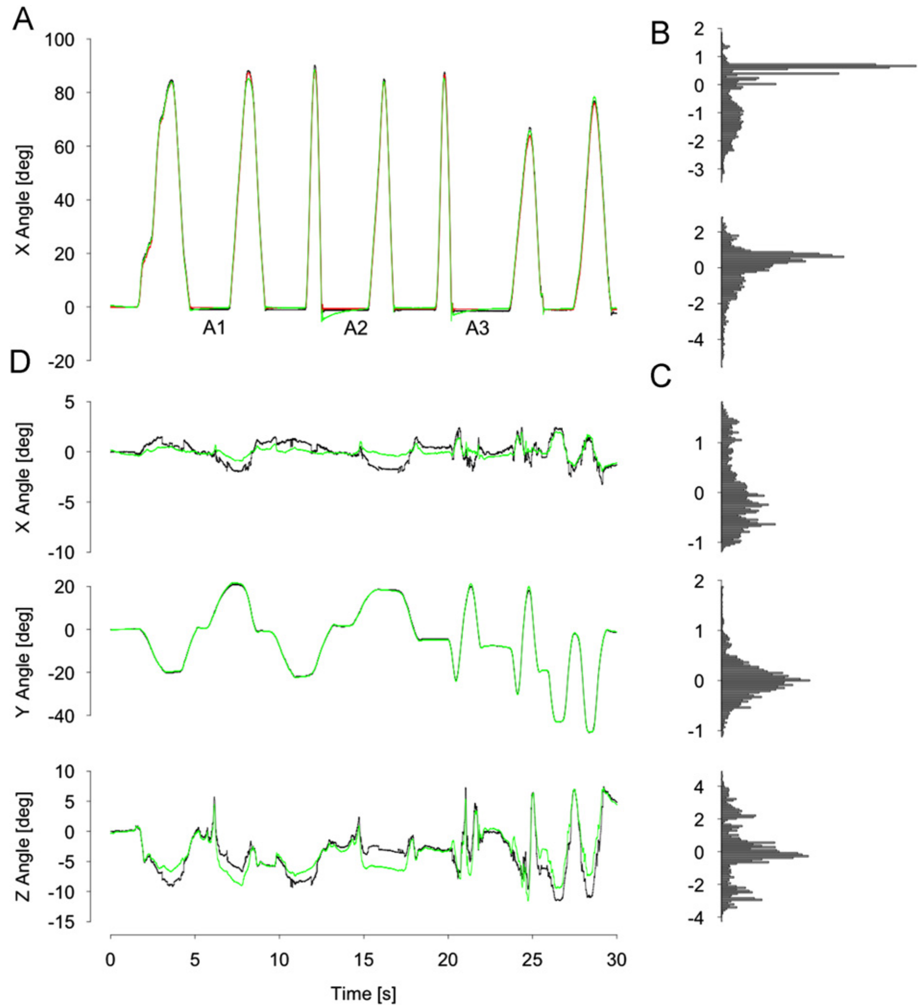

Fig. 2. Comparison between methods. (A) Time series of angular estimates from the marker-cluster based method (black), the marker-based method (red) and the inertial sensor based method (green) during rotation in flexion/extension (only one angular component is shown). Labels A1–3 denote three events that are investigated further in Fig. 3. (B) Histogram of differences (in degree) between marker-cluster based method and marker-based method. (C) Histogram of differences (in degree) between marker-cluster based method and inertial sensor based method. (D) Comparison between marker-cluster based method (black) and inertial sensor based method (green) during rotation in abduction/adduction. The three angular components (X: flexion/extension, Y: abduction/adduction, Z: internal/external rotation) are shown with the corresponding histograms of differences. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

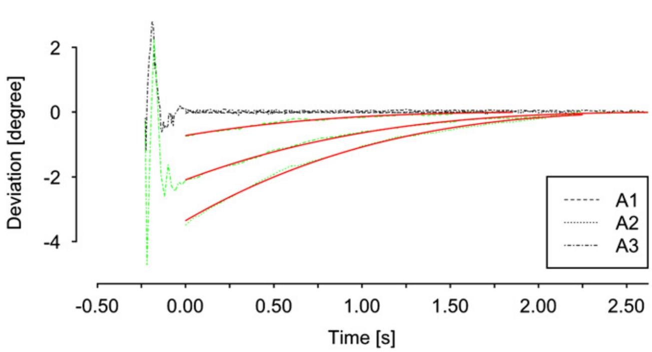

Fig. 3. Sensor response following ground contact. The figure shows 3 pairs of trajectories (marker-cluster based method, inertial sensor based method) corresponding to events A1–3 in Fig. 2. For clarity, only one pair (corresponding to event A3) is shown in full. The trajectories were realigned to the time ($t=0$) when the marker-cluster based method showed no deviation from the expected reading (0 deviation). The red curves denote the best fit (as assessed by the Bayesian Information Criterion) by a 3rd order polynomial $a(t-b)^3$ where t is time and a and b were determined using nonlinear least-squares estimation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary statistics (mean and standard deviations) of the differences (in degrees) between proposed method (M1), anatomical landmark-based method (M2) and inertial sensor based method (M3).

	Diff(M1,M2)	Diff(M1,M3)	Diff(M2,M3)
Flexion/Extension	0.0 ± 1.0	0.0 ± 1.4	-0.0 ± 1.4
Adduction/Abduction	-0.2 ± 3.1	-0.0 ± 0.4	0.3 ± 2.6
Lateral/Medial rotation	-1.0 ± 2.2	0.0 ± 1.5	1.6 ± 1.3

Table 2
Summary statistics (mean and standard deviations; $n=4$) for the maximal range (in deg.) of four hip and knee rotations of interest in infants aged 1–5 months. Hip (total) rotation denotes the rotation around the equivalent rotation axis defined in Section 3.

	Left	Right
Hip (total) rotation	71.2 ± 18.5	64.2 ± 7.3
Hip abduction/adduction	52.3 ± 11.6	58.2 ± 10.0
Hip flexion/extension	85.4 ± 36.6	66.3 ± 12.7
Knee flexion/extension	83.0 ± 18.8	64.1 ± 13.6

eigenvalue $\lambda=1$ of the matrix of roll-pitch-yaw angles). These ranges are summarized in Table 2, and are compatible with the known norms for these ranges.

4. Conclusion

The use of clusters was shown to yield robust estimates of joint rotational elements, including the hip complex, even in a soft-body dummy doll. The design of the clusters mitigates the limitations normally associated with optical tracking of stand-alone markers in infants. The Velcro enables easier application of the markers that takes only a short time to complete, and the markers within the holders are less easily accidentally removed by the infants' movements. This approach makes it possible to exploit the full power of 3D motion analysis in a clinical environment because it is not prone to interferences in the presence of metallic objects, to drifts over long periods of recording, or to slow response on ground contact. The results we report in a very limited sample of healthy infants suggest that this surface-marker cluster approach makes it possible to fully quantify infants' general movements, using both positional (direct read-out) and rotational information (estimation). This in turn will provide a quantitative and efficient way of determining atypical development in a clinical setting and making early diagnosis of motor delay more reliable. Early diagnosis of atypical motor development then affords the possibility for early therapeutic intervention.

Conflict of interest

There is no conflict of interest to report.

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