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Short communication

Between-day reliability of three-dimensional motion analysis of the trunk: A comparison of marker based protocols

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ABSTRACT

Motion capture of the trunk using three-dimensional optoelectronic systems and skin markers placed on anatomical landmarks is prone to error due to marker placement, thus decreasing between-day reliability. The influence of these errors on angular output might be reduced by using an overdetermined number of markers and optimization algorithms, or by defining the neutral position using a reference trial. The purpose of this study was to quantify and compare the between-day reliability of trunk kinematics, when using these methods.

In each of two sessions, 20 subjects performed four movement tasks. Trunk kinematics were established through the plug-in-gait protocol, the point cloud optimization algorithm, and by defining upright standing as neutral position. Between-day reliability was analyzed using generalizability theory and quantified by indexes of dependability.

Across all movement tasks, none of the methods was superior in terms of between-day reliability. The point cloud algorithm did not improve between-day reliability, but did result in 24.3% greater axial rotation angles. The definition of neutral position by means of a reference trial revealed 5.8% higher indexes of dependability for lateral bending and axial rotation angles, but 13.7% smaller indexes of dependability for flexion angles. Further, using a reference trial resulted in 8.3° greater trunk flexion angles.

Therefore, the selection of appropriate marker placement and the corresponding calculation of angular output are dependent on the movement task and the underlying research question.

1. Introduction

Three-dimensional trunk movement is commonly assessed using an optoelectronic motion capture system and reflective skin markers. Many protocols are described in the literature, differing in marker placement and calculation of angular output (Anderson, 2011; Crosbie et al., 1997; Doma et al., 2012; Frigo et al., 2003; Garrido-Castro et al., 2012; Gombatto et al., 2007; Heyrman et al., 2013; Krasnow et al., 2012; List et al., 2013; Menegoni et al., 2008; Nguyen and Baker, 2004; Preuss and Popovic, 2010; Thummerer et al., 2012; Wilken et al., 2012). The use of such protocols in longitudinal study designs, to evaluate the effect of interventions, requires high between-day reliability. Between-day reliability is influenced by biological variability, instrumental errors (Chiari et al., 2005), soft tissue artefacts (Leardini et al., 2005), and error due to marker placement (Della Croce et al., 2005). Biological variability is independent of the protocol. The magnitude of instrumental error differs between optoelectronic systems and their application (Chiari et al., 2005). Previous studies report mean instrumental error of between .1 and 5.3 mm (Ehara et al., 1997, 1995; Haggard and Wing, 1990; Klein and DeHaven, 1995; Thornton et al., 1998; Vander Linden et al., 1992). Soft tissue artefact is defined as the relative movement between a marker and the underlying bone (Leardini et al., 2005). Mean soft tissue artefacts of spinal markers have been shown to range from 9.2 to 10.7 mm during flexion and extension of the spine (Zemp et al., 2014). Error due to marker placement is caused by uncertainty in anatomical landmark position determination (Della Croce et al., 2005). The mean extent of these errors at the pelvis was 14.7–24.8 mm for inter-examiner comparisons (Della Croce et al., 1999).

The error related to marker placement is relatively large compared to other sources of error and thus having a major influence on between-day reliability. The effect of these errors on trunk kinematics however, depends on the protocol and might be

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reduced by overdetermined protocols, using a redundant number of markers and optimization algorithms (Della Croce et al., 2005), or by defining a neutral position using a reference trial (List et al., 2013) instead of anatomical landmarks.

This study investigates whether the aforementioned solutions improve between-day reliability using a random effects model and generalizability theory (Brennan, 2001). The hypotheses were (1) the day effect differs between the protocols (protocol–day interaction effect); (2) there is no protocol effect on the magnitude of trunk kinematics.

2. Methods

2.1. Subjects

Twenty subjects took part in this study (Table 1). They were recruited from the students and staff of the local university population. Overweight subjects (body mass index > 25) were excluded, on the assumption that excess weight and obesity increase soft tissue artifacts and decrease the precision of anatomical landmark detection (Moriguchi et al., 2009). The study was approved by the local ethics committee and each subject provided written informed consent prior to the first measurement.

2.2. Apparatus and marker placement

An optoelectronic motion capture system (Vicon Motion Systems, Oxford, UK) consisting of 11 infrared cameras (six MX40 and five MX3) was used to measure trunk kinematics. Data was sampled at 200 Hz and processed using Nexus 1.8.5 (Vicon Motion Systems, Oxford, UK). Twenty-two reflective markers with a diameter of 16 mm were placed on the pelvis, thorax, and spine (Fig. 1). Ten spinal markers were placed equidistantly (11% of spinal length) in a line connecting all spinal processes. Spinal length was defined as the distance between the seventh cervical vertebra and the midpoint of the posterior superior iliac spines (Ernst et al., 2013).

Table 1
Mean (standard deviation in parentheses) of subjects' characteristics.

Subjects	All ($n=20$)	Women ($n=10$)	Men ($n=10$)
Age (y)	29.5(8.5)	25.3(2.3)	33.7(10.5)
Body weight (kg)	67.3(11.0)	58.3(4.5)	76.3(7.5)
Body height (mm)	1718(100)	1636(36)	1800(69)
Body mass index (kg/m^2)	22.7(1.8)	21.8(1.7)	23.5(1.6)
Spinal length (mm)	498(24)	479(14)	516(15)
Interval between sessions (d)	4.2(2.8)	4.3(2.7)	4.1(3.1)

2.3. Procedure

Measurements were conducted in two sessions, with the second session being conducted within an interval of one to seven days. This interval was chosen to ensure that no reddening of the skin was visible at the second session. Skin marks were cleaned in the end of the first session. Age, body height, body weight and spinal length were assessed at the beginning of the first session. Anatomical landmark detection and marker placement were carried out by one of three examiners, with different examiners for each session. The order of examiners and their allocation to session one and two was balanced to avoid systematic examiner-effects. All examiners received training on marker placement and had more than two years of experience in anatomical landmark detection. After subject preparation, a standing trial was recorded as reference. Subjects were asked to stand upright and face forward comfortably. Subjects then performed four movement tasks at self-selected speed: axial rotation of the trunk to the left and right as far as possible, without moving or lifting the feet while standing upright with arms by the side; lateral bending of the trunk to the left and right side as far as possible, without moving or lifting the feet while standing upright with arms by the side; drinking from a cup placed on a table (height: 74 cm) at a predefined distance (60 cm to the front of and 30 cm to the side of the subject) and putting the cup back on the same spot, while sitting on a chair (height: 50 cm); and walking. Each movement task was repeated five times.

2.4. Data processing

The trajectories of all markers were filtered with a 4th order zero lag Butterworth filter and a cutoff frequency of 1 Hz, with the exception of the walking trials. The latter were filtered with a Woltring filter routine (Woltring, 1986) and a mean squared error of 10 mm^2. Trunk angles were defined by relative movement between the pelvis and the thorax segment. The corresponding coordinate systems and relative movements were established by using five different protocols (Supplementary File 1):

Plug-in-gait: the standard, full body plug-in-gait protocol (Vicon Motion Systems, Oxford, UK). *Adapted plug-in-gait:* the plug-in-gait protocol with altered definitions of the coordinate axes using all four markers instead of two at a time. The primary axis is defined by the normal vector of a plane fitting all markers using a least-squares approach. The secondary axis is perpendicular to the primary axis and a line connecting the midpoint of two markers respectively. The third is perpendicular to the primary and secondary axes. *Adapted plug-in-gait (reference trial):* differs from

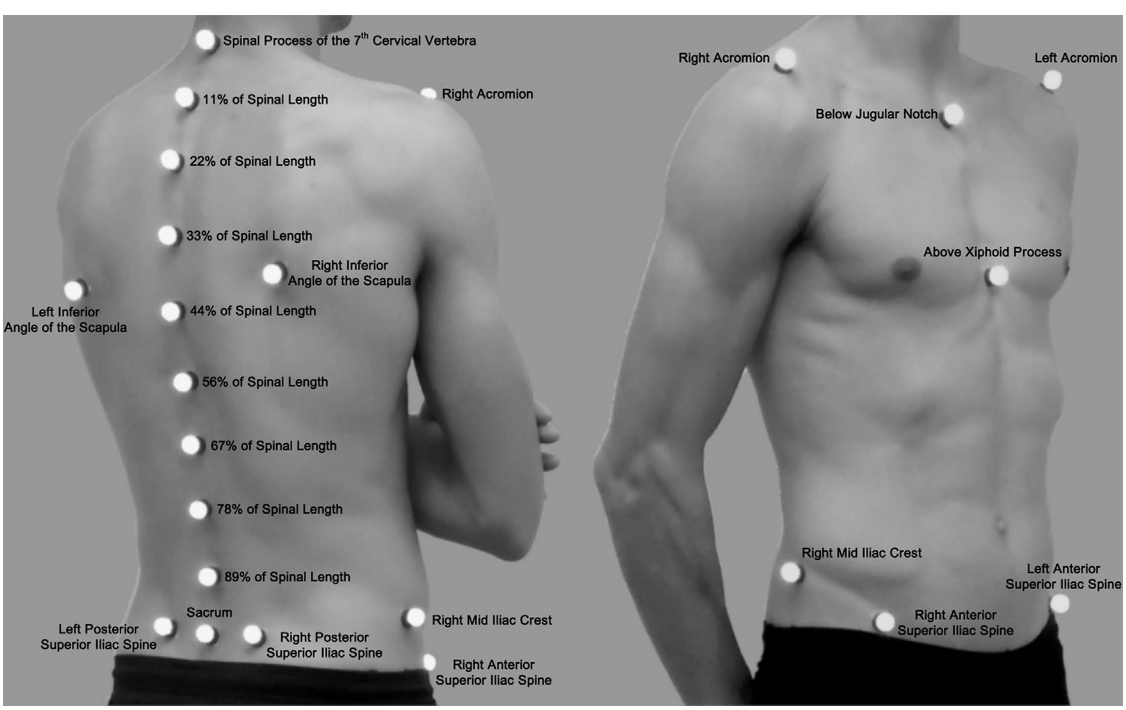

Fig. 1. Marker placement of all protocols and the corresponding anatomical landmarks.