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Short communication

Do relevant shear forces appear in isokinetic shoulder testing to be implemented in biomechanical models?

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ABSTRACT

Isokinetic dynamometers measure joint torques about a single fixed rotational axis. Previous studies yet suggested that muscles produce both tangential and radial forces during a movement, so that the contact forces exerted to perform this movement are multidirectional. Then, isokinetic dynamometers might neglect the torque components about the two other Euclidean space axes. Our objective was to experimentally quantify the shear forces impact on the overall shoulder torque, by comparing the dynamometer torque to the torque computed from the contact forces at the hand and elbow. Ten healthy women performed isokinetic maximal internal/external concentric/eccentric shoulder rotation movements. The hand and elbow contact forces were measured using two six-axis force sensors. The main finding is that the contact forces at the hand were not purely tangential to the direction of the movement (effectiveness indexes from 0.26 ± 0.25 to 0.54 ± 0.20), such that the resulting shoulder torque computed from the two force sensors was three-dimensional. Therefore, the flexion and abduction components of the shoulder torque measured by the isokinetic dynamometer were significantly underestimated (up to 94.9%). These findings suggest that musculoskeletal models parameters should not be estimated without accounting for the torques about the three space axes.

1. Introduction

Generic musculoskeletal models are highly influenced by their musculotendinous properties (Ackland et al., 2012; Scovil and Ronsky, 2006), so that care should be given to their identification. Muscles intrinsic parameters and force-length-velocity relationships are mostly identified using isokinetic dynamometers (Arampatzis et al., 2004; Herzog and ter Keurs, 1988; Lloyd and Besier, 2003). However, since the dynamometer torques are measured about a single axis, the other torques components are assumed to be negligible.

The contact forces exerted to produce a movement are yet not purely tangential to the direction of this movement (Boninger et al., 1997). In pluri-segmental cyclic tasks, like wheelchair propulsion (Bregman et al., 2009; Rankin et al., 2010) or pedaling (Bini et al., 2013; Candotti et al., 2007), perpendicular forces are also generated, reducing the mechanical efficiency of the resultant force at the handrim or at the pedal. Hence, the effectiveness index – defined as the ratio between the tangential force (*i.e.* the effective force generating the torque) and the Euclidean norm of the resultant force (Boninger et al., 1999) – is about 0.57 in wheelchair propulsion (1.0 being pure tangential resultant force) (Lin et al., 2009; Rankin et al., 2010). Such perpendicular forces come from isometric joint torques (Ellis et al., 2005). However, the latter are not measured when using isokinetic dynamometers (Herzog, 1988; Kaufman et al., 1995; Lloyd and Besier, 2003), which might be inaccurate in the specific case of muscle parameters identification. Indeed, regarding complex joints like the shoulder, muscles appear to have a plural action depending on their geometry and architecture (Herbert and Gandevia, 1995; Zajac, 1989). In that respect, Rankin et al. (2010) showed that most of the upper-limb muscles exerted, at the same time, tangential and radial forces during the pushing phase of wheelchair propulsion. For instance, in shoulder internal rotation, the pectoralis major is simultaneously assisting the internal rotation while being a transverse flexor

Abbreviations: ERcon, External Rotation, concentric mode; ERecc, External Rotation, eccentric mode; IRcon, Internal Rotation, concentric mode; IRecc, Internal Rotation, eccentric mode; RMSe, Root-mean-square error; SoC(s), System(s) of Coordinates; SPM, Statistical Parametric Mapping.

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(Marieb et al., 1993). Consequently, torque might be generated about, at least, two axes that should be accounted when aiming to calibrate musculoskeletal models, especially while performing maximal isokinetic exertions.

Our objective was to experimentally quantify the shear forces impact in estimating the overall shoulder torque, during maximal internal/external shoulder rotation movements. The torque measured by an isokinetic dynamometer was compared to the torque computed from the contact forces at the hand and elbow, while participants applied forces at these two contact points on the dynamometer attachments.

2. Material and methods

2.1. Participants

Ten untrained women with no record of upper-limb musculoskeletal disorder (26.3 ± 5.1 years; 1.65 ± 0.07 m; 64.2 ± 9.2 kg) volunteered for this study after giving their signed informed consent. The experiment was approved by the ethical committee of the Université de Montréal.

2.2. Isokinetic dynamometer instrumentation

The shoulder torque was measured and gravity-corrected by a Con-Trex® MJ isokinetic dynamometer (Physiomed, Germany). Contact forces were measured by two six-axis force sensors (2016-02A1-P/2016-02A1-C, Sensix, France) embedded into the dynamometer elbow cuff and hand grip attachments (Fig. 1).

2.3. Data collection and performances

To model the biomechanical system, twenty reflective-markers were placed on the dynamometer and its attachments (Fig. 1): 6 on the engine; 7 on the dynamometer arm; 4 on the elbow sensor; 3 on the hand sensor. These markers defined the equipment local systems of coordinates (SoCs). Seven reflective-markers were also stuck on the participants' dominant upper-limb (Fig. 2): 3 technical markers on the arm; 1 on both the anterior and posterior faces of the humeral head; 1 on each epicondyle of the elbow.

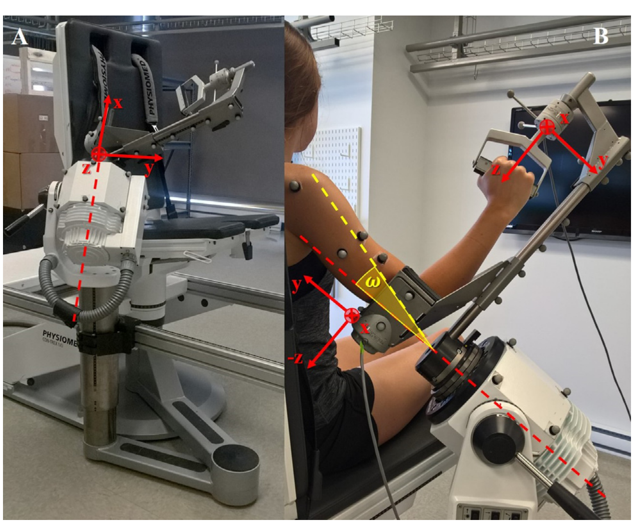

Fig. 1. Overview of the seated shoulder internal/external rotation set-up, with the two six-axis force sensors attached to the dynamometer; the engine SoC is represented in red (A). Set-up with one participant; the local SoCs of the two six-axis force sensors are represented in red (B). *Note.* The misalignment angle (ω) between the arm longitudinal axis and the engine axis has been emphasized in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Marker trajectories were collected at 100 Hz using a 7-camera-optoelectronic system (Vicon, Oxford Metrics Limited, UK). Forces were sampled at 1000 Hz. Synchronization was done by Nexus 2.4 software (Vicon Motion Systems Ltd., UK). Raw data were low-pass filtered at 20 Hz.

Participants performed a static trial with all markers visible to calculate the roto-translation matrix between the arm technical and anatomical SoCs. The two elbow markers were thereafter removed, so that participants could conveniently place their arm inside the elbow cuff, which maintained the arm longitudinal axis aligned with the engine axis. Participants were then installed in a seated position, with bent elbow and 45° of shoulder scaption, as recommended by Edouard et al. (2011) (Fig. 1). The hand grip was maintaining their hand in pronation. The largest but comfortable range of motion was defined and reported for all participants.

A first passive isokinetic trial was collected at 60°/s, measuring the sensors inertial effects (*i.e.* the forces resulting from the acceleration of the sensors) and gravity effects. Participants were instructed to be passive, while the dynamometer moved their arm throughout the range of motion. Then, four series (3 repetitions) of maximal voluntary exertions were collected at 60°/s in internal rotation in concentric (IR_{con}) and eccentric (IR_{ecc}) and external rotation in concentric (ER_{con}) and eccentric (ER_{ecc}) modes. Participants received verbal encouragements and had a 2-min rest-period between each series.

2.4. Data reduction and statistical analyses

The angle between the arm longitudinal axis and the engine axis (*i.e.* the misalignment angle, Fig. 1) was estimated by taking the inverse cosine of the scalar product of each axis normalised direction-vector (see Appendix).

After inertial- and gravity-effects corrections, the shoulder torque due to combined efforts at the hand grip and elbow cuff (τ_S) was calculated in the engine and arm respective SoC. The principle of moments and roto-translation matrices between SoCs were used. Finally, the torque measured by the dynamometer (τ_D) was projected onto the arm SoC (see Appendix).

The effectiveness index was then calculated (see Appendix). The root-mean-square (RMSe) and average errors (biases) between τ_S (sensors) and τ_D (dynamometer) were also reported in the engine and arm SoCs. The sensors shoulder torque τ_S was the reference; it was compared to τ_D expressed in the engine SoC for instrumentation and protocol validation.

Finally, *t*-test comparisons from the statistical parametric mapping (SPM) package (Friston et al., 2003) were performed in the isokinetic phase between τ_S and τ_D, in the engine and arm SoCs. The level of significance was set at $p < 0.05$.

3. Results

The mean range of motion for the 10 participants was 82.4 ± 2.1°. The mean misalignment angles were: 11.0 ± 2.1° (IR_{con}); 20.1 ± 1.6° (IR_{ecc}); 16.4 ± 1.9° (ER_{con}); 17.0 ± 1.3° (ER_{ecc}).

The contact forces applied to the hand sensor were three-dimensional (Fig. 3). In internal rotation, medial and pushing components were produced, versus lateral and pulling components in external rotation. The mean effectiveness indexes were: 0.26 ± 0.25 (IR_{con}); 0.35 ± 0.26 (IR_{ecc}); 0.54 ± 0.20 (ER_{con}); 0.27 ± 0.17 (ER_{ecc}).

In the engine SoC, SPM *t*-tests indicated no significant differences between τ_S and τ_D in axial rotation, for all the movements (Fig. 4, left column).

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