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Shoulder mechanical demands of slow underwater exercises in the scapular plane

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ABSTRACT

Background: The mechanical demands of underwater shoulder exercises have only been assessed indirectly via electromyographical measurements. Yet, this is insufficient to understand all the clinical implications. The purpose of this study was to evaluate musculoskeletal system loading during slow (30°/s) scapular plane arm elevation and lowering performed in two media (air vs water) and body positions (sitting vs supine).
Methods: Eighteen participants' upper bodies were scanned and virtually animated within unsteady numerical fluid flow simulations to compute hydrodynamic forces. Together with weight, buoyancy and segment inertial parameters, these were fed into an inverse dynamics model to obtain net shoulder moments, power and work.
Findings: Positive mechanical work done at the shoulder was 32.4% (95% CI [29.2, 35.6]) and 25.0% [22.8, 27.2] that when performing the same movement on land, supine and sitting respectively. Arm elevation was ~2.5× less demanding sitting than supine (mean 0.012 (SD 0.018) vs mean 0.027 (SD 0.012) $J \cdot kg^{-1}$, $P = 0.034$). Instantaneous power was consistently positive when sitting albeit very low during elevation (0.003 $W \cdot kg^{-1}$) whereas, when supine, it was alternately negative for short period (~1.2 s) and positive (~4.8 s), peaking at levels 3× higher (0.01 $W \cdot kg^{-1}$).
Interpretation: Performing sitting elicited concentric muscle contractions at very low effort, which is advantageous during early rehabilitation to restore joint mobility. Exercising supine, by contrast, required rapid prestretch followed by concentric force production at an overall higher mechanical cost, and is therefore better suited to more advanced rehabilitation stages.

1. Introduction

Rotator cuff disorders, regarded as the principal cause of shoulder pain and upper extremity disability, rank among the most common musculoskeletal conditions. In France, about 128 surgical operations on average have been performed daily for the past 3 years (ATIH, 2017). Protecting the postoperative shoulder from excessive load is vital, particularly early in the rehabilitation process. In that context, aquatic therapy provides formidable potential benefits. Thanks to buoyancy, the upward thrust that counteracts the action of gravity, water offers near-weightlessness exercise conditions. This unique physical property significantly accelerates the restoration of shoulder flexion range of motion as early as three weeks post-surgery (Brady et al., 2008). Furthermore, water is very viscous and thus highly dampening. Resistance rapidly decays upon cessation of movement, which is thought to dramatically reduce the risk of reinjury (Prins and Cutner, 1999).

The latest American Society of Shoulder and Elbow Therapists' consensus promotes the use of slow (30°/s) aquatic scapular plane movements to initiate aquatic therapy (Thigpen et al., 2016). The guideline is based on the observation that, at that speed, the electromyographical (EMG) activity of the deltoid and rotator cuff muscles was on average ~2–5× lower in water than on land (Castillo-Lozano et al., 2014; Kelly et al., 2000). Assuming load was proportional to muscle activity, the authors concluded that slow underwater shoulder exercises were likely safe enough for early active mobilization. However, EMG recordings only offer insight into individual muscle activation level and are poor indicators of the mechanical load on the musculoskeletal system (Winby et al., 2013; Zajac et al., 2002).

Internal load is best estimated noninvasively from inverse dynamics (van den Bogert, 1994). On land, the procedure requires the knowledge of segment inertial properties, linear and angular accelerations, as well as the ground reaction force. Eventually, it yields mechanical quantities that are superior to EMG in their capacity to analyze how muscle groups meet task mechanical requirements. Joint moments, for example, identify the dominant musculature during the observed motion (Desroches et al., 2010), and can, under different conditions, be

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representative of muscle force production and ligament loading (Kristianslund et al., 2014). The calculation of joint work, on the other hand, provides a reasonable evaluation of the actual work produced by muscles during slow movement (Sasaki et al., 2009). As such, it is a more objective and meaningful criterion of internal loading than EMG. Remarkably, inverse dynamics also has the potential to unveil the type of dynamic muscle action through the computation of joint power (Robertson and Winter, 1980). Nonetheless, a thorough inverse dynamics analysis of shoulder loading in water has never been reported. Unlike on land, accurate measurements of the hydrodynamic forces acting upon the entire upper limb surface and their respective points of force application are needed—this makes the procedure very complex and one of the major challenge of aquatic therapy (Biscarini and Cerulli, 2007).

A new methodology coupling inverse dynamics with numerical fluid flow simulations has been recently proposed to calculate instantaneous internal loading (Lauer et al., 2016). Armed with these new tools, it is also now possible, in addition to the quantities described above, to dissect the mechanical effects of buoyancy, weight, and water resistance. It is believed that modulating the action of buoyancy on the upper limb possibly influences the work done at the shoulder (Thein and Brody, 2000). This hypothesis is best viewed from a simple mechanical analysis of identical movements performed in two different positions. When sitting, buoyancy assists scapular plane arm elevation and resists arm lowering. On the other hand, buoyancy alternates between both roles when supine, temporarily assisting then resisting motion. However, the extent to which changes in body position alter shoulder load, and whether this may compromise therapy success, must be clarified.

We therefore sought to evaluate the shoulder mechanical demands of scapular plane movements performed at 30°/s in water and on land, while supine and sitting. Based on past EMG findings, we expected load in water to be roughly within 20–50% that on land. Furthermore, we hypothesized that varying body position would cause substantial changes in task mechanical demands, reflected by marked alterations in shoulder moments, power and work. Specifically, we predicted that elevation and lowering of the arm would require respectively less and more work when sitting compared to supine.

2. Methods

2.1. Participants and numerical procedure

Eighteen adults (Table 1) with no history of upper extremity injury or pain provided written informed consent to participate in the study. Sample size was determined a priori, based on effect size from a pilot study comparing total mechanical work between positions ($d = 0.83$, $n = 5$). Power analysis (G*Power 3; Faul et al., 2007) revealed that 18 participants were needed to detect similar effects using two-tailed, paired t-tests with 90% power and 5% type I error rate. Procedures were approved by the University of Porto Institutional Review Board.

Participants' upper bodies were scanned with a Mephisto 3D scanner (4DDynamics, Antwerp, Belgium). Virtual geometries were then edited and converted into computer-aided design models prior to import into ANSYS® Fluent® Release 14.5 computational fluid dynamics software (ANSYS, Inc., Canonsburg, PA, USA). Individualized geometries have

Table 1
Participant demographics. N: number of subjects. BMI: body mass index.

Gender	N	Age (years)		Height (m)		Mass (kg)		BMI (kg·m^{-2})	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Female	7	30.8	9.6	1.63	0.06	58.1	9.3	21.8	3.2
Male	11	33.1	9.0	1.80	0.09	76.5	13.2	23.6	2.7

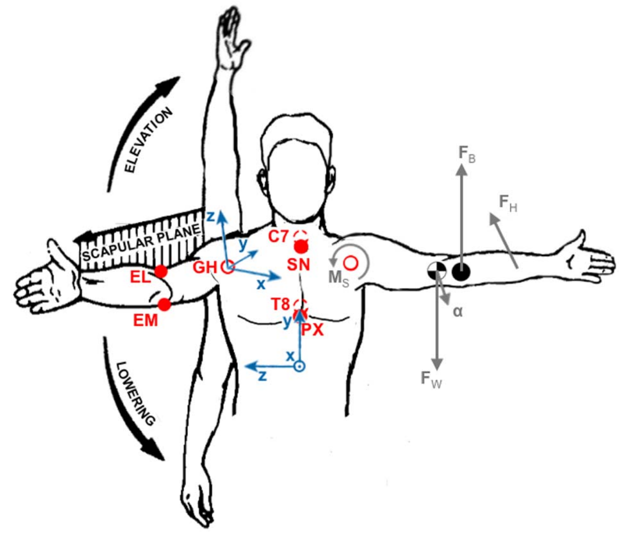

Fig. 1. Schema of the kinematics and inverse dynamics models. Continuous upper limb elevation and lowering were simulated in the scapular plane, set at an angle of 30° with the sagittal plane. The anatomical landmarks marked in red (EL: lateral epicondyle; EM: medial epicondyle; GH: glenohumeral joint center; SN: suprasternal notch; PX: xiphoid process; plus C7 and T8) were used to construct the upper limb and thorax right-handed coordinate systems (in blue). The latter is purposely represented at its wrong origin for readability. The external forces (weight, buoyancy, hydrodynamic force; $\mathbf{F}_W$, $\mathbf{F}_B$, $\mathbf{F}_H$) are denoted in gray. The resultant shoulder moment $\mathbf{M}_S$, calculated as the sum of the three other moments of force ($\mathbf{M}_W$, $\mathbf{M}_B$, $\mathbf{M}_H$), is the value of interest here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

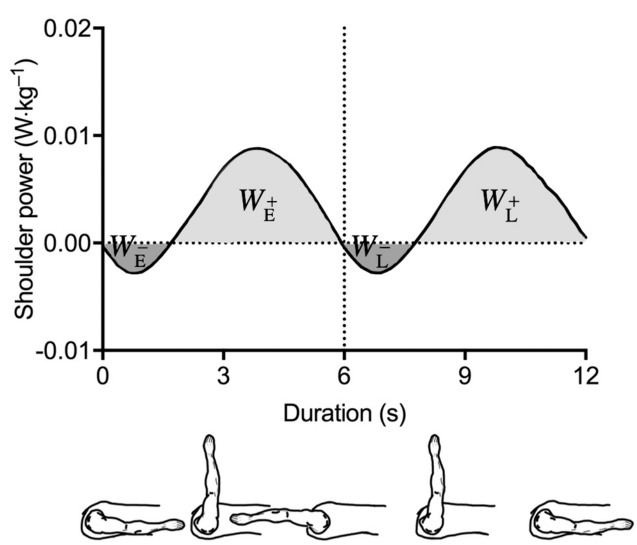

Fig. 2. Illustrative plot of instantaneous shoulder joint power during one complete cycle. Individual periods of negative (dark gray areas) and positive work (light gray areas) done at the shoulder are respectively labeled W^+ and W^-. Mechanical work values are computed separately for elevation (W_E) and lowering (W_L) by integration of the power time series with respect to time. The vertical dotted line indicates the transition from elevation to lowering of the upper limb, as exemplified by the drawing.

the advantage to make simulations sensitive to subtle interindividual differences in morphology (Lauer et al., 2016). Seven anatomical landmarks were located (see Fig. 1) to construct thorax and upper arm coordinate systems according to the ISB standards (Wu et al., 2005). Accurate knowledge of joint center location is essential to compute joint kinetics that can reliably and confidently be interpreted. Therefore, glenohumeral joint center was experimentally determined in a separate instance according to the procedure described in Lempereur et al. (2010). For that purpose, four additional markers placed distally