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Testing the assumption in ergonomics software that overall shoulder strength can be accurately calculated by treating orthopedic axes as independent

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ABSTRACT

To predict shoulder strength, most current ergonomics software assume independence of the strengths about each of the orthopedic axes. Using this independent axis approach (IAA), the shoulder can be predicted to have strengths as high as the resultant of the maximum moment about any two or three axes. We propose that shoulder strength is not independent between axes, and propose an approach that calculates the weighted average (WAA) between the strengths of the axes involved in the demand.

Fifteen female participants performed maximum isometric shoulder exertions with their right arm placed in a rigid adjustable brace affixed to a tri-axial load cell. Maximum exertions were performed in 24 directions, including four primary directions, horizontal flexion-extension, abduction-adduction, and at 15° increments in between those axes. Moments were computed and comparisons made between the experimentally collected strengths and those predicted by the IAA and WAA methods.

The IAA over-predicted strength in 14 of 20 non-primary exertions directions, while the WAA under-predicted strength in only 2 of these directions. Therefore, it is not valid to assume that shoulder axes are independent when predicting shoulder strengths between two orthopedic axes, and the WAA is an improvement over current methods for the posture tested.

1. Introduction

Ergonomics tools are often used to assess workplace tasks and determine whether the physical demand characteristics, such as load, frequency, duration and rest, are acceptable for a target percentage of the working population (Bernard, 1997). These tools have evolved over the past few decades. Previously, ergonomics was predominantly a reactive discipline, with assessments only being performed on existing tasks that were causing injuries. More recently, a proactive approach has become more prevalent, using digital human modeling (DHM) software that can interact with a virtual environment to assess the physical demands of a task prior to physically existing or a worker actually performing it (Chaffin, 2007). To do this, most ergonomics tools, such as 3DSSPP (Centre for Ergonomics, University of Michigan), Jack (Siemens, Ann Arbor, Michigan) and Delmia (Dassault Systemes, Waltham, Massachusetts), calculate the mechanical demands on the DHM in the task posture, and compare them to estimates of moment generating strength capacity.

Strength estimates are usually based on empirical evidence from over the past four decades (eg. Clarke, 1966; Schanne, 1972; Stobbe, 1982; Koski and McGill, 1994). The strength of the shoulder complex is particularly difficult to assess, due to its wide range of motion. As such, it is not feasible to experimentally determine shoulder strength capabilities; (1) of the whole population, (2) in all the possible postures and (3) in all the possible exertion directions that may be required in occupational tasks. Therefore, algorithms have been developed to predict interpolated strength capabilities in direction and posture combinations for which no empirical evidence exists. Currently, shoulder strength predictions within DHM's are generally based on empirical data from studies like Stobbe (1982), who measured both male and female strength in two directions, about each of three primary, orthopedic axes at the shoulder (abduction, adduction, horizontal flexion and extension, internal and external rotation). Five different arm

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postures were used to measure these strengths, and each was selected to optimize the muscle force length relationship for the given exertion direction.

In most current ergonomics DHM software packages, predicted strength capabilities, for resultant moment demands that are not about one of the primary axes, assume that strength, about one axis, is independent of the strength and moment demands about the other primary axes. This independent axis approach (IAA) essentially considers the shoulder to be composed of three, independent motors: one for abduction/adduction, one for horizontal flexion/extension and one for internal/external rotation. Using the IAA, the shoulder can be predicted to have strengths as high as the resultant of the maximum moment about any two or three axes. Let us take an example where a task demands both adduction and forward flexion moments be produced at the shoulder, such that the software predicts a 50th percentile abduction strength of 36.9 N m and forward flexion strength of 39.1 N m, in that posture. Under such a condition, it is possible for the software to predict a strength equal to the resultant of those two values (53.8 N m), even though this would be 37% higher than the maximum of the two involved primary axis strengths (39.1 N m).

For the IAA to be valid, the direction of each shoulder muscle force vector would have to be directly aligned with one orthopaedic axis. However, this is not the case, as most of the shoulder muscles produce moments about multiple orthopedic axes of the shoulder (Holzbaur et al., 2005). We propose that a more appropriate approach, to estimate the strength between orthopedic axes with strength data, would be to calculate the weighted average (WAA) between the strengths of those involved axes. The purpose of this study was to quantify the error associated with the IAA, and evaluate the WAA for predicting biaxial shoulder strengths in one arm posture. We hypothesize that the WAA estimates will closely resemble the measured strengths in all biaxial directions tested.

2. Methods

2.1. Participants

Fifteen right hand dominant female participants (24.1 ± 3.2 years; 166.5 ± 6.5 cm; 67.2 ± 13.4 kg), with no history of upper limb injury, were recruited for this study. All were recreationally active. Written informed consent was provided prior to testing. Approval to conduct this study was provided by the University Research Ethics Board.

2.2. Instrumentation and experimental protocol

Forces were measured using a tri-axial load cell (2224 N XYZ Sensor, Sensor Development Inc., Lake Orion, MI, USA) with a padded rigid brace (adapted from Biodex 4 attachment, Biodex Medical Systems, New York, USA) affixed to the surface (Fig. 1). This assembly was mounted to a horizontal slotted rail column (80/20 Inc., Columbia City, IN, USA), within a frame made of the same material, allowing for vertical height adjustment to accommodate each participant (Fig. 1). Participants were seated, secured across the hips with an adjustable strap, and were asked to position their right arm into the brace. The height of the load cell was adjusted such that the shoulder was in 90° of abduction. The brace had a broad adjustable strap that secured their arm just proximal to the elbow with the abducted shoulder, elbow at 90° flexion and forearm vertical. A computer monitor was situated in front of the participant to provide visual feedback during the exertions. Moment arm length was measured from the lateral edge of the acromion process to the mid-point of the rigid brace, for each individual, and used later to calculate shoulder moments.

Fig. 1. Testing apparatus and participant arm posture for both testing sessions. Visual feedback was provided on the monitor situated in front of the participant (out of frame). Moment arm length (from the acromion to the centre of the rigid pad) was recorded for each individual to ensure proper positioning on both days, and to compute shoulder moments with the forces collected by the triaxial load cell.

Participants performed exertions during three separate sessions. The first and second sessions were used to familiarize the participants to the brace used to maintain posture, and to the visual feedback, to ensure there was no effect of learning during the collection session. On the third day, participants assumed the same testing posture and were instructed to exert maximally while trying to trace the rectangular border that would represent their predicted shoulder strength when using the IAA while maintaining the testing posture. Real-time visual feedback consisted of a marker indicating their resultant force vector, and a rectangle that represented the strength envelope that would be predicted with the IAA (in two dimensions). Four repetitions of the exertion were performed, randomly starting in one of the four exertion directions (up, down, forward, backward) aligned with the two axes. Two of the four exertions were performed in a clockwise direction and two in a counter-clockwise direction. Participants had 30 s to complete two attempts of the rectangle tracing task, after which two minutes of rest were given.

2.3. Data analysis

For both sessions, shoulder moments were calculated using the measured forces, from the tri-axial load cell, and the moment arm length. For the first two sessions, the highest moments, from either testing day, were recorded and used for comparison. The experimental maximum moments for efforts in the abduction, adduction, horizontal flexion and horizontal extension directions were used as the four primary strengths to allow for the subsequent calculations of the IAA and WAA strengths. Each trial provided a measure of strength in all directions. The full cycle was divided into 24 angle ranges, in 15° increments. For each trial, the highest moment recorded within every 15° increment angle range was used to represent the strength for that range. For example, the highest moment vector magnitude recorded in the range between 7.5° and 22.5° was used to represent the strength at 15° for that trial. Then, the highest moment recorded across all four trials, was used to represent the participant's strength for each angle range.

2.3.1. Independent axis approach (IAA)

The IAA strengths, in each direction, were defined by a perimeter that was created with the four primary maximum strength