MODELLING SCAPULAR BIOMECHANICS TO ENHANCE INTERPRETATION OF KINEMATICS AND PERFORMANCE DATA IN ROWING

Caryn A. Urbanczyk[1, 2], Alison H. McGregor[1], Anthony MJ. Bull[2]

Department of Surgery & Cancer, Faculty of Medicine, Imperial College, London, UK[1]
Department of Bioengineering, Faculty of Engineering, Imperial College, London, UK[2]

Rowing involves repetitive, high intensity loading on the glenohumeral joint. Shoulder pain is associated with muscle weakness and imbalance, resulting in long-lasting overuse injuries. The goal of this study was to explore three-dimensional shoulder biomechanics during rowing to identify parameters that influence technique. Eleven athletes had their movement recorded by motion capture while using an instrumented ergometer. Kinetics and kinematics drove a computational model which output joint and muscle forces across the shoulder. Results suggest that subtle muscular changes identified by the model can be sensitively mapped to performance variables. When evaluated alongside ergometer-derived power metrics, biomechanics parameters can provide athletes and coaches a fuller picture of performance potential, injury risk, and training program efficacy.

KEYWORDS: Ergometer, Shoulder, Optical motion capture, Musculoskeletal model

INTRODUCTION: In rowing, technique influences performance, and an athlete's success depends on their ability to consistently execute effective technique. The cyclic rowing stroke motion can be qualitatively described by sequential phases: *early-drive, late-drive* and *recovery*, separated, respectively, by key stroke moments: the *catch, maximum handle force,* and the *release*. Kinematic and electromyography studies on rowers of varying experience levels, reinforce that effective technique relies on accurate sequencing of limb and trunk motion to maximize force transmission from the foot stretcher to the oar handle (Smith & Spinks, 1995). An inability to perform the stroke correctly through poor technique or fatigue affects total power output and may contribute to injury (Hofmijster, Van Soest, & De Koning, 2008). Detailed biomechanical measures of the upper body during rowing are very limited, especially analyses that examine movement beyond the sagittal plane, despite the fact that research suggests up to 40% of the velocity from the *late-drive* through the *release* comes from the upper limb (Soper & Hume, 2004). The upper body provides stability as large loads are passed up the kinetic chain across the shoulder and repetitive loading as muscles fatigue can lead to decreased technique efficiency, reduced scapular stabilization, and altered glenoid contact patterns (Bey et al., 2010). The purpose of this study was to combine optical motion capture with computational modelling to characterize trunk and shoulder biomechanical factors in ergometer rowing dynamics, to evaluate how these characteristics affect joint loading and muscle activation when modulated by rate (i.e. number of stroke cycles per minute), and to examine relationships between biomechanics parameters and performance.

METHODS: Eleven healthy volunteers participated in the study (7 female/4 male; height: 175.2±8.8 cm; mass: 73.1±8.9 kg; age: 25.8±6.6 years). All subjects were university or club athletes regularly rowing at the time of the study. Imperial College research ethics committee granted approval and written informed consent was obtained from each participant.

A 10-camera optical motion capture system (Vicon, UK) recorded kinematics at 100Hz. Twenty-six 14mm reflective markers tracked the torso, scapula, arm, and hand. (Figure 1). A scapula palpator was used during calibration to create an anatomical coordinate frame from three scapula landmarks,

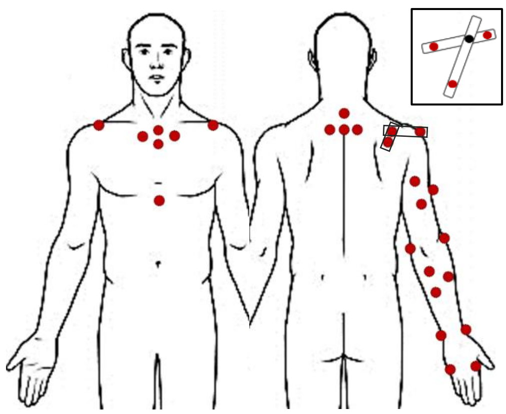

Figure 1: Anatomical marker positions, scapula tracker, and palpator (inset).

which was related to the technical frame of a rigid scapula tracker used during dynamic motion trials (Prinold, Shaheen, & Bull, 2011). Athletes performed four, 3-minute rowing trials at increasing rate (18/24/28/32 strokes per minute, spm) on an instrumented ergometer (Concept 2, VT, USA), with load cells at the handle, seat, and footplates, and a rotary encoder on the flywheel.

Synchronized motion data and external force data were processed in MATLAB (MathWorks, MA, USA). Continuous rowing trials were divided into individual strokes where the start was identified as the minimum sagittal handle position. The *catch* was identified as the onset of handle force which exceeds a threshold of 75N with a steep, increasing slope (Buckeridge, Hislop, Bull, & McGregor, 2012), the intervening period defined as *catch slip*. The *release* was defined as maximum handle displacement. Each stroke was time normalized from 0-100% of completion using a cubic spline interpolation, such that the *drive* time was from *start* (0%) to *release*, and the *recovery* time was from *release* to 100%.

Kinematics and kinetics provided input to the UK National Shoulder Model (Charlton & Johnson, 2006), which is an inverse dynamics musculoskeletal model of the upper limb comprising ninety muscle elements crossing five joints: sternoclavicular, acromioclavicular, scapulothoracic, glenohumeral, and elbow (Prinold et al., 2011). The model employs a load-sharing optimization minimising the sum of squared muscle stress and outputs joint forces, joint moments, muscle forces and activation patterns. Output measures were analyzed by two-way repeated measures ANOVA with Tukey HSD pairwise comparisons. All statistics were run in RStudio (RStudio Team, 2016).

RESULTS: *Drive* time and total stroke time decreased with increasing rate, reflected in a lower *recovery*-to-*drive* ratio (Table 1). Significant increases in timing to *catch, max handle force,* and *release* ($p<0.01$; Figure 2a), show trends that a greater proportion of time is spent in the *early-drive* phase (i.e. before *max handle force*), where cumulative shoulder joint and muscle force is highest. As rate increases there is an increase in body weight suspension at the *catch*, but no change in suspension at *max handle force* and a decrease in suspension at the *release* ($p<0.01$; Figure 2b).

Table 1: Time to reach specific key points during the stroke (mean ± std, *p<0.01; **p<0.001).

Step	Catch Slip (sec)	Time to MHF (sec)	Drive Time (sec)	Stroke Time (sec)	Recovery Time (sec)	Recovery to Drive Ratio
18	0.20±0.05	0.49±0.16	1.13±0.09*	3.30±0.09**	2.17±0.11**	1.94±0.19**
24	0.19±0.05	0.49±0.12	1.06±0.08*	2.49±0.04**	1.42±0.07**	1.35±0.13**
28	0.19±0.04	0.47±0.10	1.02±0.08	2.14±0.03**	1.12±0.07**	1.12±0.11**
32	0.19±0.03	0.44±0.09	0.97±0.09	1.90±0.05**	0.94±0.07**	0.96±0.12**

Significant changes were seen in timing and peak seat force as rate increased ($p<0.01$). At the lowest rate (18spm), peak seat force coincided with peak GH extension and internal rotation, however, as rate increased, the seat-force profile shifts and at the highest rate (32spm) peak seat force coincides with the *release* (Figure 3a). At all rates, peak GH extension and internal rotation occur immediately prior to the *release*, while peak GH abduction coincides with the *release* (Figure 3c).

Generation of peak muscle force by Trapezius (0.57±0.25kN) and Pectoralis major (1.56±0.66kN) always occurs in the *early-drive* phase, while peak force in Teres major (1.89±0.36kN) and Triceps Brachii (1.12±0.38kN) occur immediately after *max handle force*. Peak force of Latissimus Dorsi (1.04±0.30kN) and Serratus Anterior (1.26±0.35kN) occurs during *late-drive*. Subscapularis generates a sharp force peak in *late-drive* phase (1.98±0.57kN), just preceding the *release* (Figure 3b). After moving through the *release*, all scapular musculature becomes substantially unloaded and remains so throughout the *recovery*, until the start of the following stroke (Figure 3b).

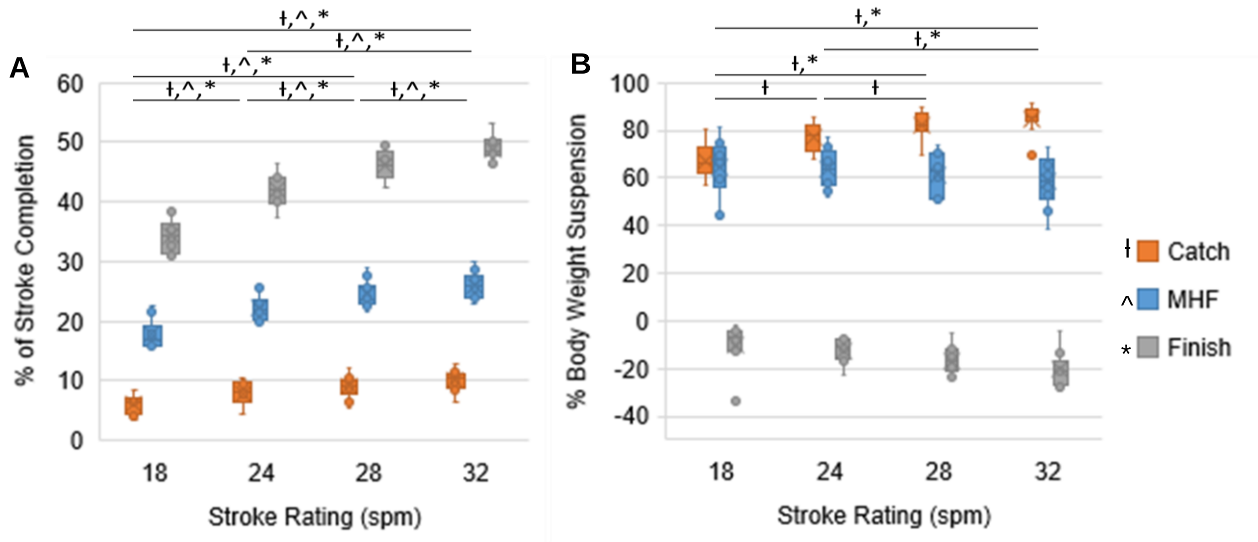

Figure 2: (A) Relative timing to reach key kinematic stroke moments at all trial ratings. (B) Percent of body weight suspension occurring at key kinematic moments [ł,*,^ p<0.01].

DISCUSSION: Results from this study highlight the relationship of muscle and joint force timing to timing of key stroke moments and ergometer-derived performance indicators. Coaches emphasize the importance of shoulder stability at the *catch* and acceleration of the arms into the *release*, and understanding how muscle activations and joint reactions correspond to traditional kinematic and power metrics offers a deeper context for optimizing rowing technique.

The scapula is pivotal in proximal to distal sequencing, transferring large forces from the footplate and legs to the hands and oar. This is accomplished most efficiently when the shoulder acts as a stable platform (Kibler, 1998). Large muscles around the shoulder are well suited to support load transfer across the GH joint and force patterns found in this study emphasize Trapezius and Pectoralis major as dominant shoulder stabilizers through *early-drive*. After *max handle force*, large contributions from Teres major support strong extension

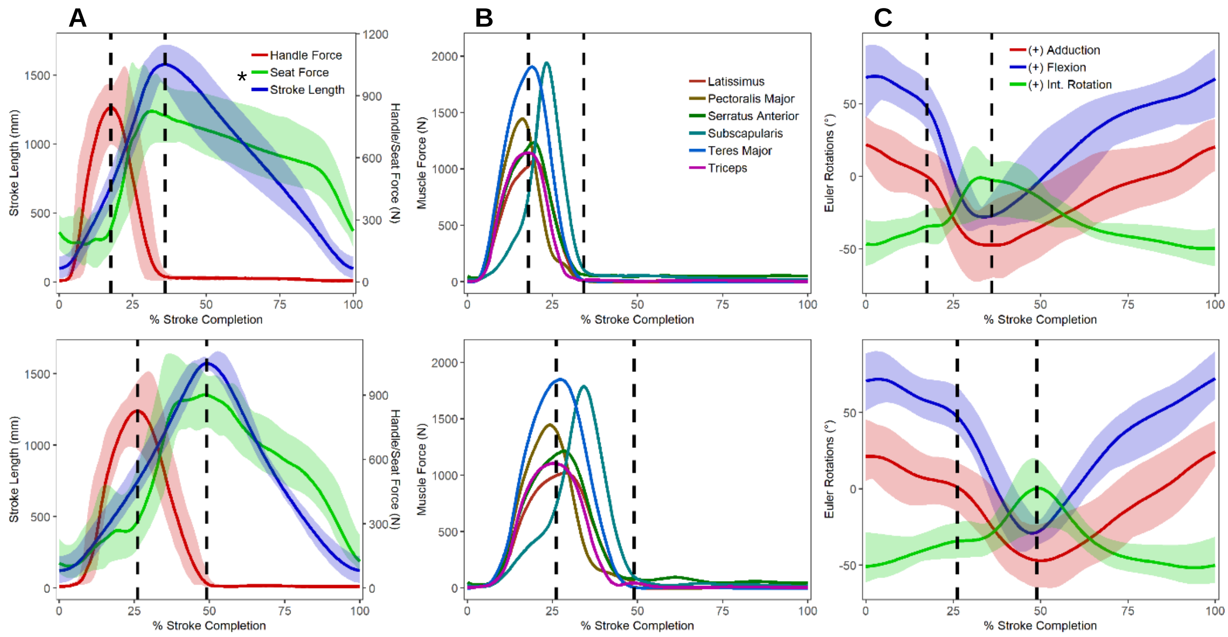

Figure 3: Kinetic and kinematic profiles (mean ± 95% CI) at lowest rate, 18spm (top row) and highest rate, 32spm (bottom row) rate. (A) Ergometer-derived power and kinematic metrics [*p<0.01]. (B) Six largest modelled upper body muscular contributions (C) Glenohumeral joint angles. Vertical dashed lines indicate timing of *max handle force* and *release* position.

and adduction of the humerus. Due to a shared tendon insertion, Teres major is functionally similar to Latissimus Dorsi, which fires together with Serratus Anterior. This finding echoes the literature (Hosea & Hannafin, 2012).

Triceps Brachii has a broad force pattern, acting initially to maintain extension of the elbow joint to support sustained tensile load transmission in *early-to-mid-drive*, working in synergistic control of the shoulder and elbow with other scapular muscles. This supports the literature that pulling the handle with elbows fully extended optimizes load transfer through the entire limb (Bompa, Borms, & Hebbelinck, 1990), yielding consistent force production over many cycles. Patterns of GH joint angle motion are comparable to those previously documented (Halliday, Zavatsky, Andrews, & Hase, 2001), although ranges of motion reported here tend to be larger in internal/external rotation and smaller in flexion/extension. Unlike as reported in Halliday (2001) GH joint rotation shows a qualitative change in peak timing of angle-profile between the lowest and highest rates (Figure 3c). Future investigations into shape differences of kinetic and kinematic stroke profiles with respect to rate will be quantified using functional data analysis techniques.

In addition to generating greater handle force by taking advantage of a direct line of action from Latissimus Dorsi, this study indicates that a strong, quick onset contraction from Subscapularis in the *late-drive* (Figure 3) facilitates final adduction of the shoulder when the arms are raised and the elbows are abducted from the torso. This pattern of engagement provides additional stabilization, centralizing the humeral head, in preparation for the abrupt change in direction and acceleration that occurs at the *release*.

CONCLUSION: Kinematic assessments have been used to analyze rowing technique, by matching movement profiles to seat-force and handle-force profiles measured on instrumented ergometers. This study has shown that these assessments can be enhanced with musculoskeletal modelling, by identifying which muscles are important and the timing of their loading, enabling sensitive delineation of internal dynamics to external kinematic changes. Such feedback can provide physiological context to guide coaches and physiotherapists in translating what a dynamic movement should feel like to help athletes achieve a specific performance output or engrain a beneficial technique modification.

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