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Kinematic and EMG analysis of horizontal bimanual climbing in humans

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ABSTRACT

Climbing is an increasingly popular recreational and competitive behavior, engaged in a variety of environments and styles. However, injury rates are high in climbing populations, especially in the upper extremity and shoulder. Despite likely arising from an arboreal, climbing ancestor and being closely related to primates that are highly proficient climbers, the modern human shoulder has devolved a capacity for climbing. Limited biomechanical research exists on manual climbing performance. This study assessed kinematic and muscular demands during a bimanual climbing task that mimicked previous work on climbing primates. Thirty participants were recruited – 15 experienced and 15 inexperienced climbers. Motion capture and electromyography (EMG) measured elbow, thoracohumeral and trunk angles, and activity of twelve shoulder muscles, respectively, of the right-side while participants traversed across a horizontal climbing apparatus. Statistical parametric mapping was used to detect differences between groups in kinematics and muscle activity. Experienced climbers presented different joint motions that more closely mimicked the kinematics of climbing primates, including more elbow flexion ($p = 0.0045$) and internal rotation ($p = 0.021$), and less thoracohumeral elevation ($p = 0.046$). Similarly, like climbing primates, experienced climbers generally activated the shoulder musculature at a lower percentage of maximum, particularly during the exchange from support to swing and swing to support phase. However, high muscle activity was recorded in all muscles in both participant groups. Climbing experience coincided with a positive training effect, but not enough to overcome the high muscular workload of bimanual climbing. Owing to the evolved primary usage of the upper extremity for low-force, below shoulder-height tasks, bimanual climbing may induce high risk of fatigue-related musculoskeletal disorders.

1. Introduction

Climbing is both an athletically and evolutionarily relevant activity to modern humans. Humans and closely related primates, such as chimpanzees, likely have a common climbing ancestry, making the biomechanics of human climbing of evolutionary and biomechanical interest (Green and Alemseged, 2012; Larson et al., 2007; Young et al., 2015). Climbing is also a popular recreational and competitive sport (Giles et al., 2006; Schöffl et al., 2010). Recent increases in climbing participation and accompanying performance and injury concerns amplify the need for biomechanical assessment of climbing (Folkl, 2013; Jones et al., 2008). Climbing often involves the upper and lower extremity, intermittent bimanual climbing phases, and typically includes overhead reaches (Folkl, 2013; Larson, 1988; Lewis et al., 2001; Roseborrough and Lebec, 2007). The modern human shoulder has become primarily adapted for non-locomotor behaviors, with muscle architecture that produce less force output, and boney orientations and muscle insertions that are not designed for elevated postures, despite a possible climbing ancestry (Inman et al., 1944; Lewis et al., 2001; Mathewson et al., 2014; Thorpe et al., 1999; Veeger and van der Helm, 2007). The particular loading consequences of climbing on the upper extremity are especially pertinent, as it is not a typical musculoskeletal exertion of the upper extremity.

The human shoulder is highly susceptible to pathology in climbing and overhead postures. Overhead postures increase the physical loading of soft tissues of the upper extremity (Dickerson et al., 2015; Grieve and Dickerson, 2008; Lewis et al., 2001; Rashedi et al., 2014). These postures cause rapid fatigue and become even more problematic as workload increases or the posture is sustained for longer periods (Ebaugh et al., 2006; Jones et al., 2008). Climbers experience an extremely high rate of upper extremity injury (Folkl, 2013; Nelson et al., 2017), with some reports of rotator cuff tendonitis and impingement as high as

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33% (Rooks, 1997). Conversely, other primates regularly assume and maintain low and high force overhead postures without developing shoulder pathology (Potau et al., 2007; Stern and Larson, 2001). Despite a likely arboreal common ancestor with chimpanzees, the human shoulder appears to have devolved a capacity for overhead climbing postures (Young et al., 2015).

Modern human climbing performance has not been objectively and biomechanically explored. However, primate climbing performance has been investigated, owing to its relevance to evolution. Analyses of chimpanzee behaviors such as horizontal bimanual climbing, vertical climbing and hanging exist (Larson and Stern, 1986; Larson et al., 1991; Stern and Larson, 2001; Usherwood et al., 2003). Horizontal bimanual climbing, in which the weight of the entire body mass is often supported by the shoulder and upper extremity, require powerful and prolonged activity from the muscles of the shoulder girdle (Larson and Stern, 1986; Lewis et al., 2001). The demands of ancestral behaviors such as horizontal bimanual climbing on the human musculoskeletal system are largely unknown. Analysis of climbing biomechanics, and cross-species comparison, may provide insight into the potential evolution and current musculoskeletal limits of the human shoulder.

The purpose of this study was to document and contextualize right-side human kinematics and select electromyographical activity in experienced and inexperienced climbers during horizontal bimanual climbing, intended to mimic evolutionarily relevant climbing behaviors in chimpanzees. It is hypothesized that experienced climbers will employ kinematic patterns that are more similar to climbing primates and efficient, and lower normalized EMG activation across all muscles.

2. Methods

Right-side kinematic and EMG comparisons between two human participant groups were conducted in the present study. The set up for collecting bimanual climbing data followed methodologies used in previous work conducted by researchers examining ape kinematics and kinetics during brachiation. The study was approved by the University of Waterloo Research Ethics Board and all participants provided informed consent.

2.1. Climbing apparatus

A TRX suspension training system (Fitness Anywhere LLC, CA, USA) served as the support structure for the climbing task. Eight rungs were attached to the TRX system (Fig. 1) in horizontal sequence, equally spaced 40 cm apart (Stern and Larson, 2001). The rungs were located 2.4 m off the floor.

2.2. Participants

30 participants were recruited from the University of Waterloo population, 15 experienced climbers, and 15 inexperienced non-climbers, with 12 males and 3 females in each group. Experienced climbers were required to have at least 2 years of climbing experience and partake in climbing activities regularly, at least once every two weeks. Climbing experience was varied, and typically included wall and rock climbing, and bouldering. Inexperienced non-climbers were classified into the participant group if they had never, or only participated in climbing activities a few isolated times. To ensure task completion, all participants were pre-screened by inquiring about their upper extremity exercise routine and perceived strength, and confidence in their ability to complete a strenuous upper extremity or climbing task. Only those that displayed moderate proficiency in the task were included in the study.

2.3. Electromyography

Disposable Ag/AgCl surface electrodes with an inter-electrode distance of approximately 2 cm (Noraxon USA Inc., Arizona, USA) were placed on the right, dominant side over the anterior and posterior deltoid, pectoralis major clavicular and sternal head, supraspinatus, infraspinatus, upper and middle trapezius, latissimus dorsi, serratus anterior, biceps brachii and triceps brachii following standard placement guidelines (Cram and Kasman, 1998) (Table 1). A reference electrode was placed on the sternum. Prior to electrode placement, the skin over each muscle belly was prepared by shaving hair and cleansing the area with isopropyl alcohol. Electromyography was collected using a wireless Noraxon TeleMyo 4200T G2 (Noraxon USA Inc., Arizona, USA) sampled at 3000 Hz. Two 5-second muscle-specific maximum voluntary isometric exertions (MVC) were completed on all right-side muscles

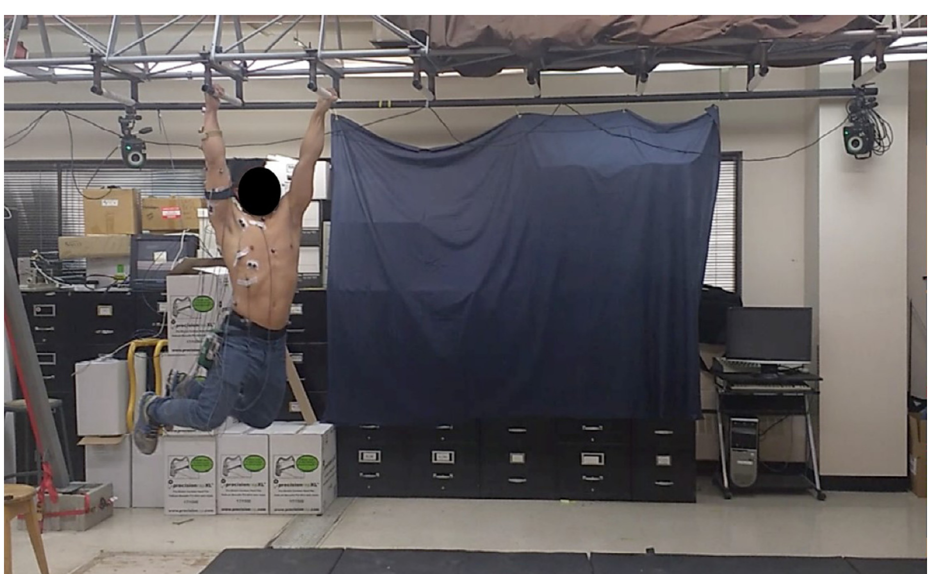

Fig. 1. Study participant performing the climbing task on the R + TRX climbing apparatus. Solid rungs were affixed to the TRX Suspension training system, approximately 40 cm apart. Each participant used the rungs as climbing supports to traverse across the TRX, alternating support hand with each upcoming rung.

Table 1
EMG electrode placement, following Cram and Kasman (1998), and maximum voluntary exertion protocol for each of the collected muscles.

Muscle	Electrode placement	MVC Action
Pectoralis major (clavicular)	Between sternoclavicular joint and the caracoidus process, 2 cm below the clavicle (on an angle down and laterally)	With shoulder horizontally abducted and externally rotated to 90° and elbow flexed to 90° (fingers point to ceiling), horizontal adduction is resisted
Pectoralis Major (Sternal)	6 cm above the nipple	With shoulder horizontally abducted to 30° with elbow flexed to 90°, horizontal adduction is maximally resisted
Anterior Deltoid	2–4 cm below the clavicle, parallel to muscle fibres	With the shoulder flexed to 90°, maximally flex against resistance applied by a research assistant
Posterior Deltoid	2 cm below lateral border of scapular spine, oblique angle toward arm (parallel to muscle fibers)	With shoulder abducted to 90° and externally rotated, and elbow flexed to 90° (fingers point to ceiling), extension is resisted
Supraspinatus	Midpoint and 2 finger-breadths superior to scapular spine	With shoulder abducted 5° and elbow extended (thumb pointing up), abduction is maximally resisted
Infraspinatus	Parallel to spine of scapulae, approximately 4 cm below, over the infrascapular fossa	With arm at side and elbow bent to 90°. External rotation of the arm is maximally resisted
Upper Trapezius	2/3 on the line between the trigonum spinae and the 8th thoracic vertebrae, 4 cm from muscle edge, at approximately a 55° oblique angle	With head turned to right side, subject resists shoulder abduction at 90° with elbow extended (thumb down to floor)
Middle Trapezius	Placed at 50% of the distance between the medial border of the scapula and the spine, at the level of T3, over the muscle belly	With elbow extended and the shoulder placed in 90° abduction and lateral rotation, subject resists shoulder abduction.
Latissimus Dorsi	6 cm below the inferior angle of the scapula	With shoulder horizontally abducted and externally rotated to 90° and elbow flexed to 90° (fingers point to ceiling), adduction is resisted
Serratus Anterior	Below 5th rib, anterior to the latissimus dorsi	In a push-up position, subject anteriorly curls their thorax and protracts their scapula
Biceps Brachii	Above the center of the muscle, parallel to the long axis	With the elbow flexed to 90°, subject resists flexion maximally
Triceps Brachii	On the posterior portion of the upper arm, located medially	With the elbow flexed to 90°, subject maximally resists extension

(Table 1). This data was used to normalize EMG. A rest period of at least 2 min was given between each MVC.

2.4. Motion capture

Eight Vicon MX20 infrared cameras (Vicon, Oxford, UK) were used to collect three-dimensional pelvic, thoracic, upper arm and forearm motion at a sampling rate of 50 Hz. Seventeen passive reflective markers were placed on right side upper extremity landmarks, following ISB recommendations (Wu et al., 2005) – 7th cervical vertebra spinous process, 8th thoracic vertebra spinous process, suprasternal notch, xiphoid process, medial and lateral epicondyles, ulnar and radial styloids, 2nd metacarpophalangeal, 5th metacarpophalangeal, left and right acromion, left and right anterior superior iliac spine, left and right posterior superior iliac spine, and the 5th lumbar vertebra spinous process. In addition, two three-marker clusters affixed to rigid plates were placed on the upper arm and forearm to track upper arm and forearm movement, respectively.

2.5. Experimental protocol

EMG electrodes were applied first, followed by two rounds of MVC trials. Next, motion capture markers were affixed to the participant, a calibration trial was performed, and the overhead bimanual climbing protocol was conducted. For each trial, participants began at one end of the climbing apparatus and were asked to swing across all eight rungs, alternating the contact arm with each ladder rung (Fig. 2). Each participant was asked to traverse the ladder apparatus at least five separate times. Participants were given time to practice, and rest periods of approximately 2 min between each climbing attempt. Participants climbed at their own pace.

2.6. Data processing

EMG and kinematic data were processed using custom-built MATLAB (Mathworks, USA) programs. From each climbing trial, one to two full right arm climb cycles were extracted. A full right arm climb cycle represented right-hand support with a rung to a subsequent right arm contact with another rung, and included both a "support" and "swing" phase (Fig. 2). The timing of each right arm climb cycle was determined using hand marker acceleration. The right arm support phase was identified as the time when the three-dimensions of hand markers passed and stayed below an acceleration threshold of 0.05 m/s.

Both trial and MVC EMG was high pass filtered at 30 Hz to remove potential heart rate and motion artifact (Drake and Callaghan, 2006). The signal was linear enveloped with a single-pass Butterworth low pass filter at 4 Hz (Mathiassen et al., 1995). The peak value was extracted from MVC trials to determine the maximum activation for each muscle and used to normalize each muscle to percent MVC through a right arm swing cycle. Each signal was then time-normalized to 100% of the climb cycle, from initial right arm contact with the rung (0%) to the subsequent ipsilateral right arm contact (100%). All the time-normalized trials for each participant were averaged to produce a single mean climb cycle trial for each muscle.

Kinematic data was dual-pass filtered with a Butterworth low-pass filter at a cut-off frequency of 6 Hz (Winter, 2009). Local coordinate systems (LCS) were defined for each body segment following definitions outlined by the International Society of Biomechanics (Johnson et al., 1996; Wu et al., 2005). LCS were created for the right forearm, right humerus, thorax, and pelvis, and used to determine intersegmental elbow, thoracohumeral and trunk angles from relative rotation matrices. All intersegmental descriptions and three-dimensional rotations were based on Euler rotation sequences recommended by the International Society of Biomechanics (Wu et al., 2005). Like the EMG data, kinematic data was time normalized from right arm contact with a rung to the subsequent right arm contact with a rung. All normalized climb cycles were combined within each participant to create a mean representative climb cycle waveform for each participant.

2.7. Data analysis

Anthropometric differences between participant groups were assessed using independent t-tests in Minitab (Minitab, Inc, USA).

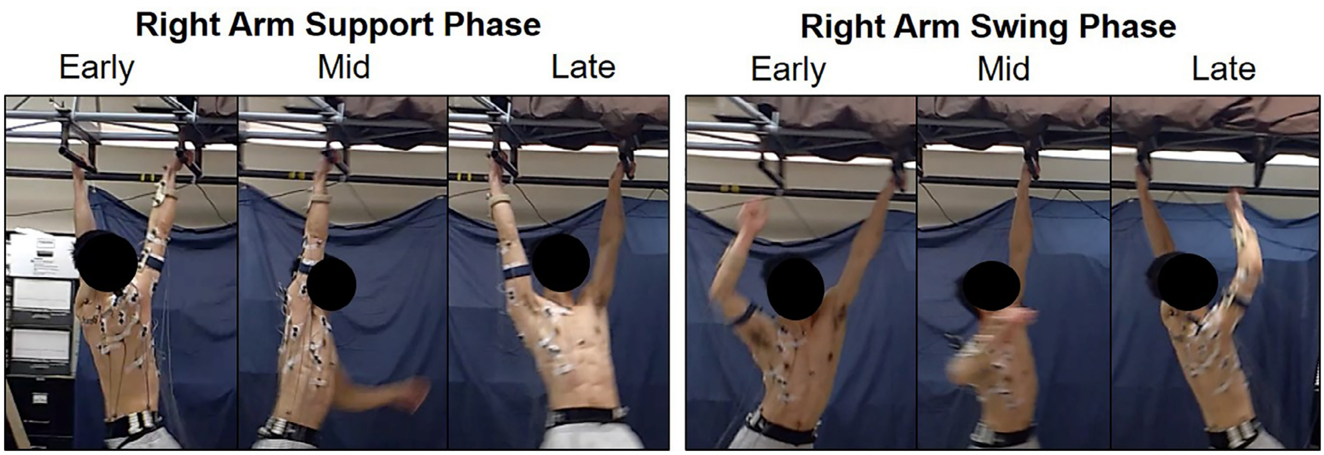

Fig. 2. A full, right-arm climb cycle performed on the climbing apparatus, broken into six static time points. A full climb cycle includes a support phase followed by a swing phase. Early support begins once the right hand makes contact with the support rung. In mid-support the right hand is the sole support limb, as the left-arm is in swing phase. In late support, the contralateral left-hand makes contact with a support rung, and the right hand prepares for releases from the support rung to being early swing. Right arm swing phase continues until the right hand makes contact with the next sequential support rung.

One-dimensional statistical parametric mapping (SPM) was used to detect differences between groups in intersegmental angles and muscle activity across the normalized climb cycle time-series curves (Pataky, 2012). SPM assesses topological regional effects in the spatiotemporal domains of a continuous waveform, making it well suited to many biomechanical measures (Pataky, 2012). Using the open-source code for MATLAB (www.spm1d.org), a series of two-tailed t-tests ($\alpha = 0.05$) determined differences between participant groups for each intersegmental angle and muscle. The SPM method distinguished all specific time points in the climb cycle time-series where statistically significant differences between groups exist.

3. Results

No differences existed between the participant groups in anthropometrics, through the non-climbers were slightly heavier (Table 2).

3.1. Kinematics

Differences were noted between participant groups in elbow, thoracohumeral and trunk angles. Though the differences were subtle, the inexperienced non-climbers were less flexed in swing ($p = 0.045$), and more externally rotated ($p = 0.021$) at the elbow in swing (Fig. 3A, C). Though not significant, the inexperienced climbers were also less flexed and more externally rotated in support phase (Fig. 3A, C). The inexperienced non-climbers were in significantly greater thoracohumeral elevation by approximately 10° in early support only ($p = 0.046$), but this trend did extend through most of support (Fig. 3E). Inexperienced climbers were also in more trunk extension in support ($p = 0.003$), and swing phase ($p = 0.0001$) (Fig. 3G). The experienced climbers were in more right lateral flexion ($p = 0.001$) throughout the support phase, including during left swing (Fig. 3H).

Table 2
Anthropometric means (and standard deviations) for both participant groups. Arm span was from tip of fingers to shoulder. Arm girth was taken at the widest part of the upper arm.

	Climbers	Non-climbers	p-value
Sex (M/F)	12M/3F	12M/3F	n/a
Age (yrs)	25(3.6)	24.3(2.89)	0.793
Height (m)	1.71(0.08)	1.75(0.075)	0.909
Mass (kg)	66.9(9.05)	74.71(12.7)	0.096
Right arm span (m)	0.78(0.09)	0.88(0.04)	0.851
Right arm girth (m)	0.29(0.02)	0.30(0.03)	0.956

3.2. Electromyography

Differences also existed between participant groups in the EMG amplitude (Fig. 4). At the late support to early swing exchange, infraspinatus ($p = 0.001$), anterior deltoid ($p = 0.001$), posterior deltoid ($p = 0.001$), biceps brachii ($p = 0.001$), pectoralis major sternal head ($p = 0.001$), upper trapezius ($p = 0.002$) and middle trapezius ($p = 0.017$) amplitude was higher in the inexperienced group (Fig. 4). Inexperienced climbers activated supraspinatus ($p = 0.003$), anterior deltoid ($p = 0.001$), biceps brachii ($p = 0.001$), triceps brachii ($p = 0.001$), and latissimus dorsi ($p = 0.001$) in the late swing to early support exchange (Fig. 4). The experienced climbers activated serratus anterior more in swing phase ($p = 0.0001$) (Fig. 4L). There was high normalized EMG activation accompanied by high variability in both participant groups, with some muscles, like pectoralis major (sternal head), greatly exceeding measured MVC by nearly 100% (Fig. 4). Normalized EMG values were often sustained above 15–20% MVC throughout the climb cycle.

4. Discussion

Though the differences between participant groups in arm motion were small, they represent different functional strategies that likely affected the efficiency of the climbing task completion. Arm range of motion is extremely important in climbing behaviors, with a particularly special combination of large range of motion, strength and stability existing in hominoid primate forearms and shoulder (Sarmiento, 1987, 1988; Stern and Larson, 2001). The experienced climbers elevated their arm less throughout the entire climb cycle, and flexed and internally rotated at the elbow more in support and mid-swing. These postures served to raise the body, increase reach range, shift the torso toward the trailing support limb and create potential energy for use during swing phase (Larson and Stern, 1986; Larson and Stern, 2013; Sarmiento, 1987, 1988; Stern and Larson, 2001). These kinematic strategies also more closely mimicked primate climbing patterns (Larson and Stern, 1986; Larson et al., 1991). Differences in kinematic

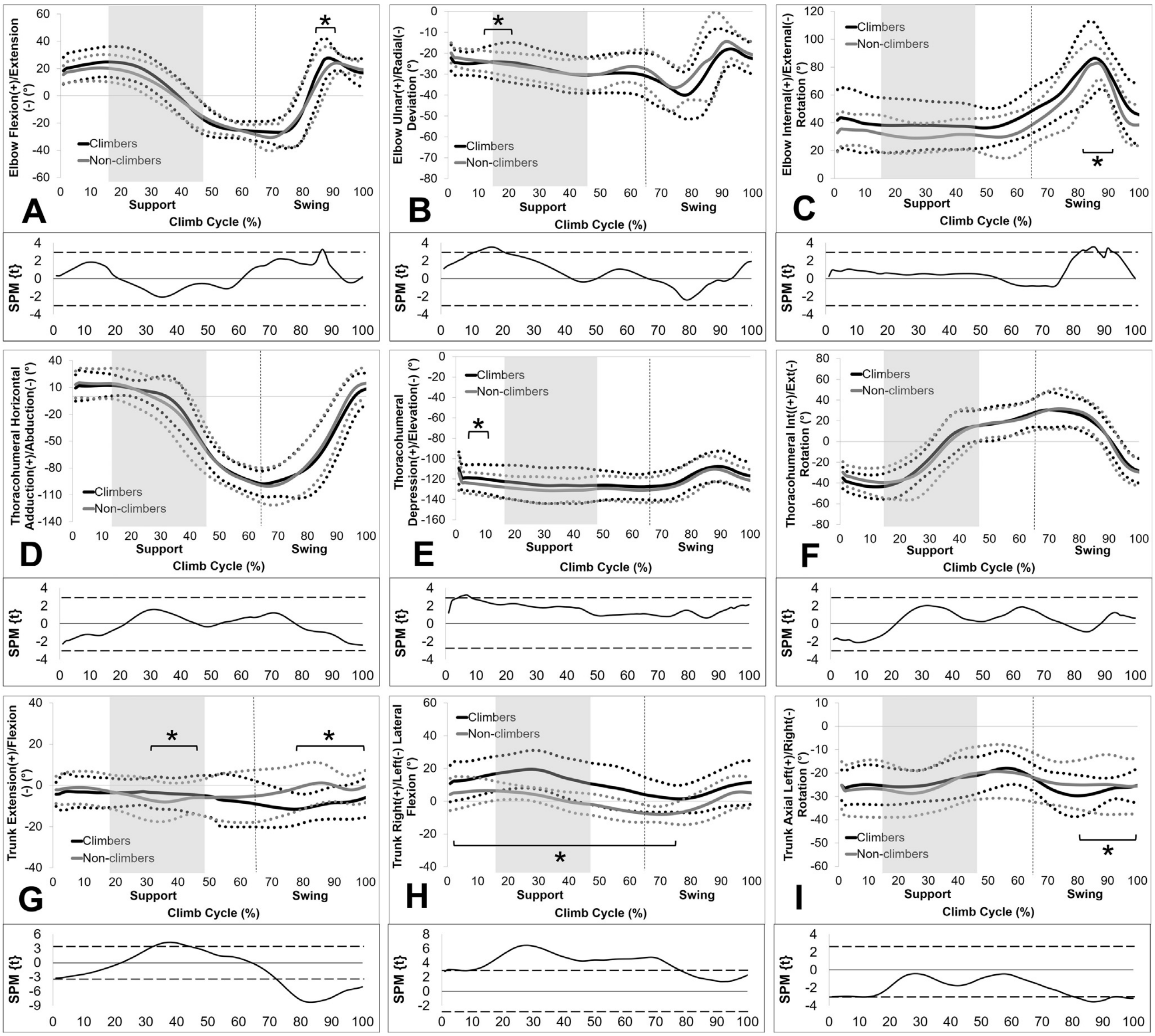

Fig. 3. Averaged participant group elbow (left), thoracohumeral (middle) and trunk (right) intersegmental angles for experienced climbers (black) and inexperienced non-climbers (grey), time normalized to a full climb cycle. Right arm support and swing phase are parsed by the vertical dashed line. Left arm swing phase occurs within right arm support phase and is denoted in the greyed area. One standard deviation for each group is represented by dotted lines in the corresponding colour. Associated SPM z-scores are reported below averaged waveforms, with critical z-scores denoted by dashed lines. Where z-scores exceed the critical value, significant differences between groups are denoted with an asterisk (*) on the averaged waveforms over the area where they exist.

strategies could indicate more muscular ability in experienced climbers to enable more primate-like behaviors such as pulling themselves up to improve reach position for swing phase, increasing forward momentum, or both. As chimpanzees and other primates who bimanually climb as a form of habitual locomotion have efficient kinematics, this result suggests climbing experience in modern humans can lead to moderately more efficient and evolutionarily relevant kinematics.

There was limited range of motion about the trunk. This was expected, as the torso remains fairly upright and is used in brachiation for mechanical purposes, contributing to the mass on the end of the pendular arms (Larson, 1988; Usherwood et al., 2003). Primates often create trunk extension or lateral flexion in the contralateral direction of arm swing to create a greater "drop" in center of gravity and increased acceleration in the forward direction, fueling the forward momentum of swing phase (Fleagle, 1977; Larson et al., 1991; Larson and Stern, 1986). That neither climbing group performed trunk extension and lateral flexion concurrently may have been due to limited need for increased forward momentum to perform the present, self-paced climbing task.

The climbing task required large muscle forces to counter traction and the moments created about the joints during support and swing phase (Larson et al., 1991; Usherwood et al., 2003). Of the muscles recorded in this study, those active in support represented some of the larger upper extremity and torso muscles, capable of producing large muscle forces to stabilize the elbow and shoulder (Inman et al., 1944). Activity from these muscles during support ensured the glenohumeral joint reaction force was directed into the glenoid cavity by controlling scapular and humeral rotation and translation, and elbow flexion to raise the body (Larson and Stern, 1986; Larson and Stern, 2013; Larson et al., 1991; Veeger and van der Helm, 2007). The majority of muscles were also active from mid to terminal swing, when the arm swings forward and elevates again to reach the next support rung (Larson et al., 1991). In

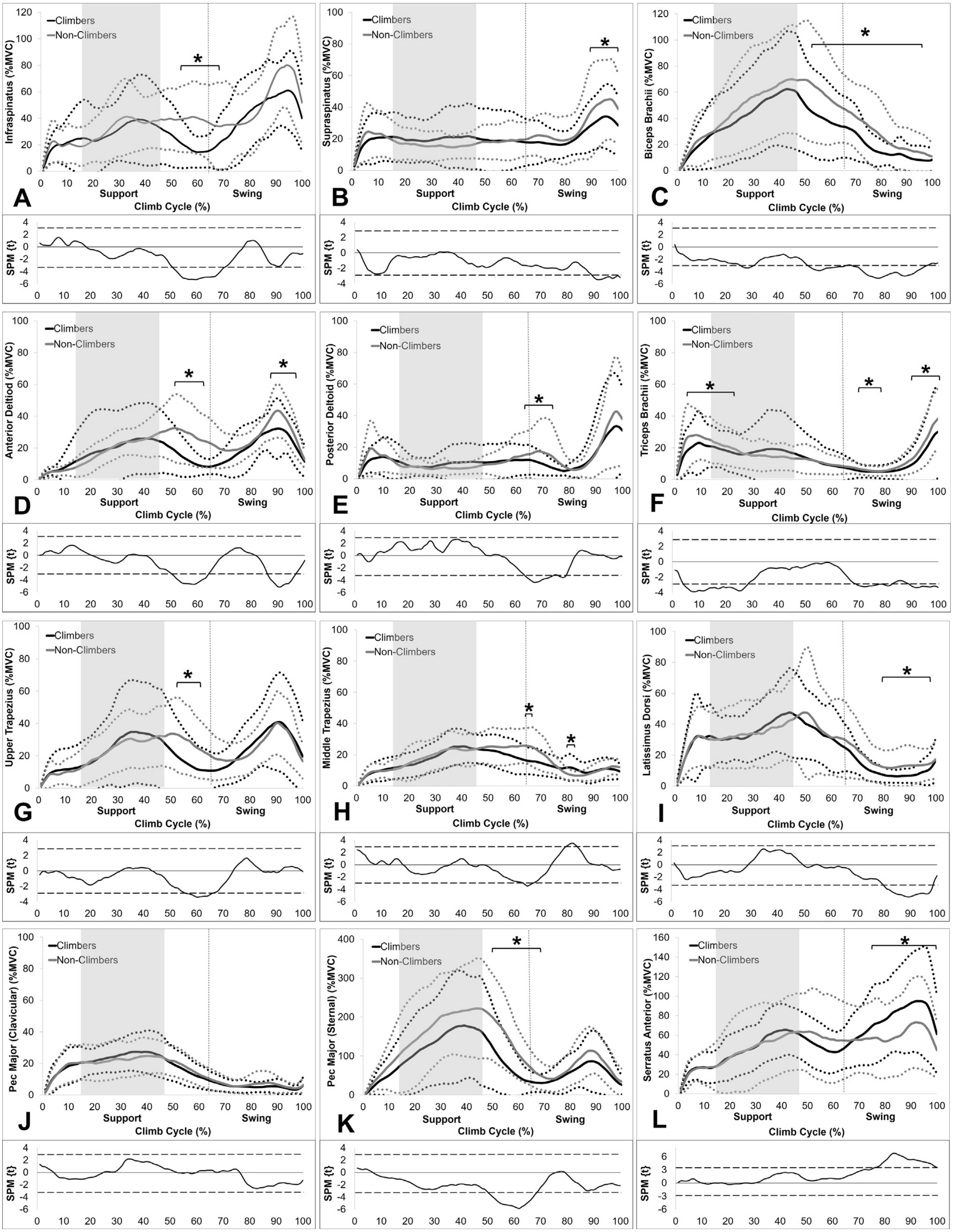

Fig. 4. Averaged participant group normalized muscle amplitudes for experienced climbers (black) and inexperienced non-climbers (grey), time normalized to a full climb cycle. Right arm support and swing phase are parsed by the vertical dashed line. Left arm swing phase occurs within right arm support phase and is denoted in the greyed area. One standard deviation for each group is represented by dotted lines in the corresponding colour. Associated SPM z-scores are reported below averaged waveforms, with critical z-scores denoted by dashed lines. Where z-scores exceed the critical value, significant differences between groups are denoted with an asterisk (*) on the averaged waveforms over the area where they exist.

this phase of the climb cycle, shoulder muscles acted to control lateral rotation and protraction of the scapula, elevation and horizontal adduction of the humerus, and extension of the elbow (Larson et al., 1991; Larson and Stern, 1986).

Group differences in EMG were often most pronounced at the support-to-swing and swing-to-support exchange. EMG has been measured on primates performing bimanual climbing, however comparisons between human and chimpanzee EMG measures can only be done subjectively, due to methodological differences. The timing of bursts of human muscle activity in both participant groups all followed similar patterns as previously reported chimpanzee EMG, in the anterior deltoid, infraspinatus, supraspinatus, upper and middle trapezius and serratus anterior (Larson et al., 1991; Larson and Stern, 1986). The experienced climbers more often decreased muscle activation from terminal support to early swing phase. The reduced activity at this transition phase in experienced climbers more closely mimicked chimpanzee EMG activity, which occurs in more distinct, phasic bursts (Larson et al., 1991; Larson and Stern, 1986). Early swing is the least taxing point of a climb cycle, and represents a transient opportunity for a brief muscle activity reduction. Owing to their lack of climbing experience, increased muscle activity in the inexperienced non-climbers may have been a potential strategy to improve joint stability, compensating for lower task skill level and confidence (Lugo et al., 2008; Veeger and van der Helm, 2007).

Though the inexperienced non-climbers generally had higher muscle activity, experienced climbers activated serratus anterior more in swing phase. The serratus anterior is a very large muscle in climbing primates, and one of the most important contributors to scapular motion. During swing phase, the serratus anterior stabilizes the descent of the scapula and thorax as the forward motion of the body elevates the arm toward a support rung (Larson et al., 1991; Jenkins et al., 1978; Stern et al., 1980). Experienced rock climbers have less static scapular lateral rotation than individuals without rock climbing experience for the same arm elevation (Roseborrough and Lebec, 2007). It has been suggested that this may be due to muscular adaptations that place greater demands on the serratus anterior. Activation of the serratus anterior by experienced climbers may indicate a training effect that engages an evolutionarily important muscle more primarily during climbing.

Unlike in chimpanzees, the recorded EMG amplitudes indicated that climbing is a taxing, and potentially injurious, behavior in modern humans. Though typically similar in timing of activity bursts, human muscle activity is much higher than equivalent primate muscles throughout the bimanual climb cycle (Larson and Stern, 1986; Larson et al., 1991). Muscle activations were often above 20% MVC, and exceeded MVC in some muscles. Humans have an evolved lower relative proportion of muscle mass and force production ability in the upper extremity relative to their body mass than chimpanzees and other primates. The modern, non-weight-bearing human upper extremity has become primarily adapted for low-force, often below shoulder-height behaviors (O'Neill et al., 2017). Resultantly, humans experience much greater rates of rotator cuff pathology (Codman, 1934; Roberts, 1974; Potau et al., 2009; Thorpe et al., 1999; Walker, 2009). The sustained muscle activation amplitudes during the present climbing study support previous work indicating that climbing is physically demanding due to being overhead and weight-bearing (Lewis et al., 2001; Nelson et al., 2017; Roseborrough and Lebec, 2007; Wright et al., 2001). Rock climbers have a 75–90% upper extremity injury rate due to overuse (Wright et al., 2001). More than 30% of recreational rock climbers reportedly experience rotator cuff tendonitis or impingement (Rooks, 1997). Therefore, the muscular workload necessary to complete the climbing task, even in experienced climbers, is likely unsustainable over extended periods of time without the onset of fatigue-related disorders such as subacromial impingement (Chopp et al., 2010; Cote and Bement, 2010).

5. Limitations

There are a number of limitations to the present study. The rung spacing was fixed. While this choice mimicked primate studies, the anthropometric variability of the human participants in the present study could have affected the ability of each to perform the task. Participant climbing pace was not fixed. While this experimental decision was made to keep the task feasible for all participants, it would affect kinematics and muscle activation. Further studies with modifiable rung spacing, or correlation of subject specific anthropometrics, such as arm length, with kinematic and muscular strategies, and monitored or controlled climbing speed could provide greater insight into bimanual climbing task variability by removing confounding factors in the present study. Further, understanding the three-dimensional biomechanics of other, more common arboreal methods, like rock climbing and quadrupedal climbing, could be both clinically and evolutionarily relevant. The present kinematic analysis did not include scapular and clavicular kinematics. These bones were tracked during the data collection phase, but due to technical limitations, it was not possible to reliably reconstruct these bones and derive relative three-dimensional rotations. Climbers have altered static scapular rotations compared to non-climbers (Roseborrough and Lebec, 2007). Analyzing dynamic three-dimensional scapular kinematics would be a highly useful clinical, biomechanical, and physical anthropological endeavor. As well, due to experimental constraints, only one limb was measured. As this task is bimanual, it would be valuable in future work to measure motion and EMG both arms. Similarly, not all muscles surrounding the shoulder were collected. Muscles not considered due to methodological capacity and constraints include some considered important to climbing, such as parts of the deltoid, trapezius and rotator cuff. Of the muscles collected, some greatly exceeded their MVC, such as pectoralis major (sternal head), while others like serratus anterior came very close to MVC. This may be indicative of an insufficient MCV task. The normalized amplitudes of these muscles should be considered with some caution. Finally, lower extremity kinematics were not analyzed in the present study. Due to safety concerns, the rungs were set at a height that allowed some participants to reach the rungs while standing on the ground. This may have affected the choice to flex the hip and knees to ensure ground clearance. Flexion of the lower extremity can provide potential energy to increase forward swing momentum, and is often utilized by climbing primates to improve climbing efficiency (Fleagle, 1977; Larson et al., 1991; Larson and Stern, 1986). While the experimental set-up may have forced hip and knee flexion in some participants, it likely improved climbing mechanics. Future work should consider analysis of climbing at greater heights, and lower extremity mechanics during climbing.

6. Conclusion

Bimanual climbing is a difficult task for modern humans. Of the groups studied, those experienced with climbing used slightly more efficient climbing kinematics and reduced muscular activity. Some of these strategies were similar to those reported in primates that climb as a form of locomotion, though humans maintained higher muscle activity overall. Evolutionary changes to upper extremity musculoskeletal morphology have made climbing an injury-riddled behavior in modern humans (Lewis et al., 2001; Potau et al., 2009; Rooks, 1997). That humans have devolved the anatomy to locomote as climbers is intrinsically tied to the adaptation to low load, below shoulder-height repetitive upper extremity tasks (O'Neill et al., 2017). Further research on comparative biomechanics of evolutionary climbing could explain why specific musculoskeletal adaptations devolved at the human shoulder and how they affect modern human climbing capacity.

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Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Chopp, J.N., O'Neill, J.M., Hurley, K., Dickerson, C.R., 2010. Superior humeral head migration occurs after a protocol designed to fatigue the rotator cuff: a radiographic analysis. J. Shoulder Elbow Surg. 19 (8), 1137–1144.
Codman, E.A., 1934. The Shoulder. Rupture of the supraspinatus tendon and other lesions I or about the subacromial bursa. Boston, Massachusetts.
Cote, J.N., Bement, M.K.H., 2010. Update on the relation between pain and movement: consequences for clinical practice. Clin. J. Pain 26 (9), 754–762.
Cram, J.R., Kasman, G.S., 1998. Introduction to Surface Electromyography. Aspen Publishers Inc, Gaithersburg, MD.
Dickerson, C.R., Meszaros, K.A., Cudlip, A.C., Chopp-Hurley, J.N., Langenderfer, J.E., 2015. The influence of cycle time on shoulder fatigue responses for a fixed total overhead workload. J. Biomech. 48 (11), 2911–2918.
Drake, J.D., Callaghan, J.P., 2006. Elimination of electrocardiogram contamination from electromyogram signals: an evaluation of currently used removal techniques. J. Electromyogr. Kinesiol. 16 (2), 175–187.
Ebaugh, D.D., McClure, P.W., Karduna, A.R., 2006. Scapulothoracic and glenohumeral kinematics following an external rotation fatigue protocol. J. Orthopaedic Sports Phys. Therapy 36 (8), 557–571.
Fleagle, J.G., 1977. Brachiation and biomechanics: The siamang as example. Malay Nat. J. 30, 45–51.
Folkl, A.K., 2013. Characterizing the consequences of chronic climbing-related injury in sport climbers and boulderers. Wilderness Environ. Med.
Giles, L.V., Rhodes, E.C., Taunton, J.E., 2006. The physiology of rock climbing. Sports Med. 36 (6), 529–545.
Green, D.J., Alemseged, Z., 2012. Australopithecus afarensis scapular ontogeny, function, and the role of climbing in human evolution. Science 338 (6106). 514-417.
Grieve, J.R., Dickerson, C.R., 2008. Overhead work: identification of evidence-based exposure guidelines. Occup. Ergon. 8 (1), 53–66.
Inman, V.T., Saunders, J.B.C.M., Abbott, L.C., 1944. Observations of the function of the shoulder. J. Bone Joint Surg. 26, 1–30.
Jenkins Jr, F.A., Dombrowski, P.J., Gordon, E.P., 1978. Analysis of the shoulder in brachiating spider monkeys. Am. J. Phys. Anthropol. 48, 65–76.
Johnson, G.R., Spalding, D., Nowitzke, A., Bogduk, N., 1996. Modelling the muscles of the scapula morphometric and coordinate data and functional implications. J. Biomech. 29, 1039–1051.
Jones, G., Asghar, A., Llewellyn, D.J., 2008. The epidemiology of rock-climbing injuries. British Journal of Sports Medicine. 42, 773–778.
Larson, S.G., 1988. Subscapularis function in gibbons and chimpanzees: implications for interpretation of humeral head torsion in hominoids. Am. J. Phys. Anthropol. 76, 449–462.
Larson, S.G., Stern Jr, J.T., 1986. EMG of scapulohumeral muscles in the chimpanzee during reaching and "arboreal" locomotion. Am. J. Anatomy 276, 171–190.
Larson, S.G., Stern Jr, J.T., 2013. Rotator cuff muscle function and its relation to scapular morphology in apes. J. Hum. Evol. 65, 391–403.
Larson, S.G., Stern Jr, J.T., Jungers, W.L., 1991. EMG of serratus anterior and trapezius in the chimpanzee: Scapular rotators revisited. Am. J. Phys. Anthropol. 85 (1), 71–84.
Larson, S.G., Jungers, W.L., Morwood, M.J., Sutikna, T., Jatmiko, Saptomo E.W., Due, R. A., Djubiantono, T., 2007. Homo *Floresiensis* and the evolution of the hominin shoulder. J. Hum. Evol. 53, 718–731.
Lewis, J., Green, A., Yizhat, Z., Pennington, D., 2001. Subacromial impingement syndrome. Has Evolution failed us? Physiotherapy 87 (4), 191–198.
Lugo, R., Kung, P., Ma, C.B., 2008. Shoulder Biomechanics. European Journal of Radiology. 68 (1), 16–24.
Mathewson, M.A., Kwan, A., Eng, C.M., Lieber, R.L., Ward, S.R., 2014. Comparison of rotator cuff muscle architecture between humans and other selected vertebrate species. J. Exp. Biol. 217, 261–271.
Mathiassen, S.E., Winkel, J., Hagg, G.M., 1995. Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies – a review. J. Electromyogr. Kinesiol. 5 (4), 197–226.
Nelson, C.E., Rayan, G.M., Judd, D.I., Ding, K., Stoner, J.A., 2017. Survey of hand and upper extremity injuries among rock climbers. Hand. 12 (4), 389–394.
O'Neill, M.C., Umberger, B.R., Holowka, N.B., Larson, S.G., Reiser, P.J., 2017. Chimpanzee super strength and human skeletal muscle evolution. PNAS 114 (2), 7343–7348.
Pataky, T.C., 2012. One-dimensional statistical parametric mapping in Python. Comput. Methods Biomech. Biomed. Eng. 15 (3), 295–301.
Potau, J.M., Bardina, X., Ciurana, N., 2007. Subacromial space in African great apes and subacromial impingement syndrome in humans. Int. J. Primatol. 28, 865–880.
Potau, J.M., Bardina, X., Ciurana, N., Camprubí, D., Pastor, J.F., de Paz, F., Barbosa, M., 2009. Quantitative analysis of the deltoid and rotator cuff muscles in humans and great apes. Int. J. Primatol. 30, 697–708.
Rashedi, E., Kim, S., Nussbaum, M.A., Agnew, M.J., 2014. Ergonomic evaluation of a wearable assistive device for overhead work. Ergonomics 57 (12), 1864–1874.
Roberts, D., 1974. Structure and function of the primate scapula. In: Jenkins, F.A. (Ed.), Primate Locomotion. Academic Press, New York, pp. 171–200.
Rooks, M.D., 1997. Rock climbing injuries. Sports Med. 23 (4), 261–270.
Roseborrough, A., Lebec, M., 2007. Differences in static scapular position between rock climbers and a non-rock climber population. North Am. J. Sports Phys. Therapy 2 (1), 44–50.
Sarmiento, E.E., 1987. The phylogenetic position of *Oreopithecus* and its significance in the origin of the Hominoidea. Am. Museum Novitates 2881, 1–44.
Sarmiento, E.E., 1988. Anatomy of the hominoid wrist joint: its evolutionary and functional implications. Int. J. Primatol. 9, 281–345.
Schöffl, V., Morrison, A., Schwarz, U., Schöffl, I., Kupper, T., 2010. Evaluation of injury and fatality risk in rock and ice climbing. Sports Med. 40, 657–679.
Stern Jr, J.T., Pare, E.B., Schwartz, J.M., 1980. New perspectives on muscle use during locomotion: electromyographic studies of rapid and complex behaviors. J. Am. Osteopath. Assoc. 80, 287–291.
Stern Jr, J.T., Larson, S.G., 2001. Telemetered electromyography of the supinators and pronators of the forearm in gibbons and chimpanzees: implications for the fundamental positional adaptation of hominoids. Am. J. Phys. Anthropol. 115, 252–268.
Thorpe, S.K.S., Crompton, R.H., Gunther, M.M., Kerr, R.F., Alexander, R.M., 1999. Dimensions and moment arms of the hind- and forelimb muscles of common chimpanzees. Am. J. Phys. Anthropol. 110, 179–199.
Usherwood, J.R., Larson, S.G., Bertram, J.E.A., 2003. Mechanisms of force and power production in unsteady ricochetal brachiation. Am. J. Phys. Anthropol. 120, 364–372.
Veeger, H.E.J., van der Helm, F.C.T., 2007. Shoulder function: The perfect compromise between mobility and stability. J. Biomech. 40 (10), 2119–2129.
Walker, A., 2009. The strength of great apes and the speed of humans. Curr. Anthropol. 50 (2), 229–234.
Winter, D.A., 2009. Biomechanics and Motor Control of Human Movement. John Wiley & Sons Inc., New Jersey, USA.
Wright, D.M., Royle, T.J., Marshall, T., 2001. Indoor rock climbing: who gets injured? Br. J. Sports Med. 35 (3), 181–185.
Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion. – Part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992.
Young, N.M., Capellini, T.D., Roach, N.T., Alemseged, Z., 2015. Fossil hominin shoulders support an African ape-like last common ancestor of humans and chimpanzees. PNAS 112 (38), 11829–11834.