Received: 14 May 2020 | Revised: 10 July 2020 | Accepted: 14 July 2020

DOI: 10.1111/sms.13780

ORIGINAL ARTICLE

WILEY

Avoiding high-risk rotator cuff loading: Muscle force during three pull-up techniques

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Funding information
Biotechnology and Biological Sciences Research Council

Abstract

Heavily loaded overhead training tasks, such as pull-ups are an effective strength training and rehabilitation exercise requiring high muscle forces maintained over a large range of motion. This study used experiments and computational modeling to examine loading patterns during three different pull-up variants and highlighted risks to vulnerable musculoskeletal structures. Optical motion tracking and a force platform captured kinematics and kinetics of 11 male subjects with no history of shoulder pathology, during performance of three pull-up variants—pronated front grip, pronated wide grip, and supinated reverse grip. UK National Shoulder model (UKNSM) simulated biomechanics of the shoulder girdle. Muscle forces and activation patterns were analyzed by repeated measures ANOVA with post-hoc comparisons. Motor group recruitment was similar across all pull-up techniques, with upper limb depression occurring secondary to torso elevation. Stress-time profiles show significant differences in individual muscle patterns among the three pull-up variants, with the most marked differences between wide grip and reverse grip. Comparing across techniques, latissimus dorsi was relatively more active in wide pull-ups ($P < .01$); front pull-ups favored activation of biceps brachii and brachialis ($P < .02$); reverse pull-ups displayed higher proportional rotator cuff activation ($P < .01$). Pull-ups promote stability of the shoulder girdle and activation of scapula stabilizers and performing pull-ups over their full range of motion is important as different techniques and phases emphasize different muscles. Shoulder rehabilitation and strength & conditioning programs should encourage incorporation of all three pull-up variants with systematic progression to provide greater global strengthening of the torso and upper limb musculature.

KEYWORDS
athletic training, biomechanics, motion analysis, musculoskeletal modeling, rehabilitation, shoulder

1 | INTRODUCTION

Pull-ups are a commonly used strength training and rehabilitation activity for various sports including gymnastics and rock climbing.[1,2] This learned skill involves a heavily loaded upper limb moving through a large, overhead, range of motion, and variations in hand orientation and grip width are thought to target different upper body muscles.[3,4] Common injuries among athletes regularly performing such overhead tasks include impingement, tendonitis, and rotator cuff tears,[5] which may be due, in part, to the large forces required to actuate the pull-up movement. Rotator cuff damage can be caused by exposure to repetitive loading,[6] and biceps tendonitis among overhead athletes may be exacerbated by high stress in both brachialis and biceps brachii.[2] Kinematic factors such as high humeral elevation, increased humeral internal rotation, and decreased scapular posterior tilt are also thought to contribute to impingement injuries.[7-10] Previous kinematic research has examined potential positions of injury risk in three pull-up variants, demonstrating large glenohumeral internal/external rotations with a reverse grip and reduced range of scapular protraction/retraction in wide grip, compared to front grip, both of which are movement patterns linked to increased risk of sub-acromial impingement.[11] However, kinematic analysis alone lacks information about shoulder muscle contributions to forces and contact patterns at the glenohumeral (GH) joint. Muscle activation is important in understanding injury risk, particularly in vulnerable overhead positions.[6] Surface electromyography (EMG) can measure relative magnitude of muscle contractions, but technical limitations in accessing the deeper rotator cuff muscles where injuries are most common[12,13] necessitates the use of musculoskeletal modeling to quantify joint and muscle biomechanics. There are few instances of electromyography derived kinematic analyses being applied to pull-ups[4,14-16] and only one previous study has utilized an inverse dynamics modeling approach.[17]

The aim of this study was to quantify, with musculoskeletal modeling, loading of key upper limb and torso muscles during several pull-up variants; to examine the effect of different kinematic strategies on muscle recruitment; and to highlight potential injury risks in concentric loading of vulnerable structures in these tasks.

2 | METHODS

Eleven healthy male subjects with no history of shoulder pathology participated in the study (age = 26.8 ± 2.4 years, BMI = 22.2 ± 2.2, height = 1.80 ± 0.06 meters). All subjects had been performing pull-ups as part of a regular training regime (>3 years training experience) at the time of the study. The Imperial College joint research compliance office (JRCO) ethics review committee granted approval for this study and written informed consent was obtained from each participant prior to testing.

2.1 | Apparatus

A free-standing pull-up apparatus was placed at the center of a large motion capture volume. External kinetic data were collected with a force platform recording at 1000 Hz (Kistler), placed underneath the pull-up frame. Kinematic data were collected with a 9-camera optical motion tracking system recording at 200 Hz (Vicon). Twenty-one retro-reflective passive markers were placed on relevant anatomical landmarks of the thorax, clavicle, humerus, and forearm, and a scapula tracker incorporating three markers was placed along the scapular spine.[18] Technical coordinate frames were used to define each body segment to minimize the effects of skin motion artifact[19-21] and a least squares sphere-fitting method without bias compensation was used to calculate functional joint centers.[22,23] Coordinate frames for the torso, humerus, forearm, and scapula were defined as described by ISB recommendations.[24] An Euler rotation sequence of X-Z′-Y″ (ie, abduction, flexion, and rotation) was used to calculate humerothoracic motion, while scapulothoracic movement was calculated with a Y-X′Z″ (ie, internal rotation, upward rotation, and posterior tilt) rotation sequence.

2.2 | Protocol

After warm-up and application of reflective markers, calibration trials for bony landmarks were captured: (1) at rest with the arms by the side, (2) at 90° of humerothoracic elevation in the scapular plane, and (3) at maximal coronal plane elevation. Anatomic landmarks of the scapula were directly measured using a scapular palpator.[18,25] Motion trials included five repetitions of three different pull-up grip techniques (15 pull-ups total), performed in a randomized order: (1) *front* pull-ups with pronated grip at shoulder width, (2) *reverse* pull-ups with supinated grip at shoulder width, and (3) *wide* pull-ups with pronated grip at lateral 22° angled portions of bar (Figure 1). A 30 seconds rest break was enforced every three repetitions to mitigate fatigue effects. Subjects were instructed to perform a maximal upward movement across a full range of upper limb motion, while keeping the knees flexed 90° posterior to the torso. Three of five trials from each pull-up technique per subject were selected for further analysis, based on quality of motion capture reconstruction, minimizing marker occlusion.

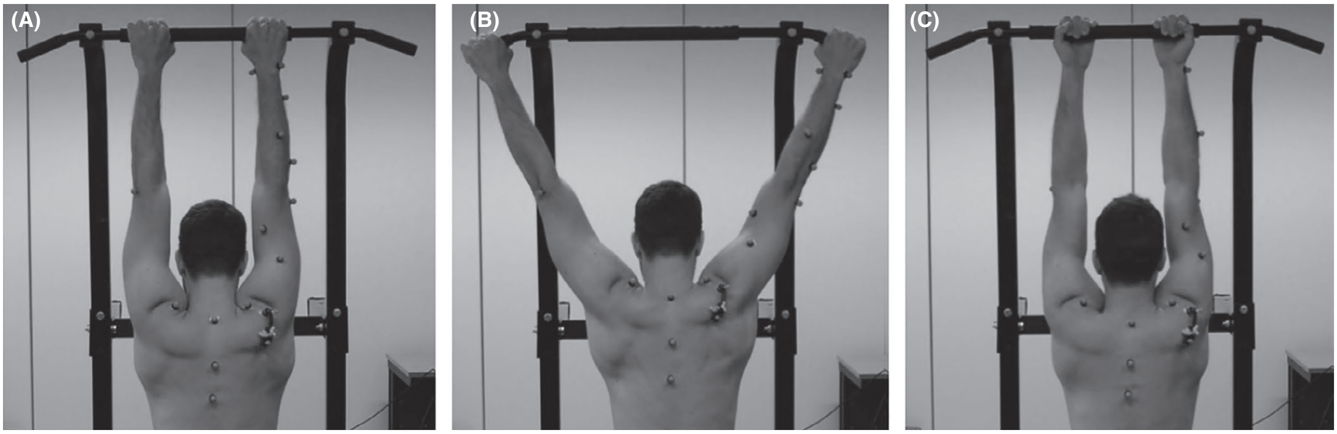

FIGURE 1 Grip location and orientation on the bar of the free-standing pull-up apparatus during each of the three pull-up variants: (A) front grip, (B) wide grip, and (C) reverse grip

2.3 | Data analysis and statistics

Kinematic and kinetic data were reconstructed in Nexus 1.8.5 (Vicon). 4th order low-pass Butterworth filters were used to smooth marker trajectories ($F_{cutoff} = 4.7$ Hz) and force platform signals ($F_{cutoff} = 10$ Hz). Data were time normalized from zero to one hundred percent of task completion using a cubic spline interpolation (MATLAB 2017b, MathWorks). The upward movement of the pull-up activity was considered, where the start (0%) was selected as the first force peak generated upon movement initiation, and task completion (100%) was identified as the minimum of the last force trough.[11] Measured pull-up force was assumed to act perpendicular to the pull-up bar and had equal distribution of force through left and right hands (Figure 1). Repeated measures ANOVA was used to test for significant differences between pull-up variants, with Tukey HSD post-hoc correction for pair-wise comparisons ($\alpha = .05$).

2.4 | Musculoskeletal modeling

The UK National Shoulder model (UKNSM) was used to simulate biomechanics of the clavicle, scapula, humerus, and forearm.[26] Briefly, each of the long bones was scaled homogenously based on segment length. The scapulothoracic gliding plane/ thorax ellipse was scaled based on subject height and measurements of the scapula during calibration. The UKNSM optimizes muscle load sharing by minimizing the sum of squared muscle stress and to accommodate this heavily loaded activity, an upper bound on muscle strength was not imposed.[27] Kinematic optimization minimized least squares differences between calculated and measured joint rotations while the medial scapula border was constrained to not penetrate the thorax ellipse and the glenohumeral joint force vector was constrained to fall within the glenoid rim, approximated by an ellipse. This constraint prevents dislocation of the humeral head by imposing some co-contraction.[28]

3 | RESULTS

3.1 | Average muscle stress profiles

Stress-time profiles indicate during which portion of the movement individual muscles are most active and how those patterns vary with pull-up technique (Figure 2). Muscle recruitment distribution across all the pull-up variants showed that trapezius (Trap), infraspinatus (Inf), and brachialis (Brac) are relatively more stressed at the beginning of the pull-up action, while latissimus dorsi (LD), teres major (TMaj), and biceps brachii (Bic) work predominately through the mid-range, and triceps brachii (Tri) and subscapularis (Sub) become most active toward the end of the upward movement (Figure 2). Compared to total muscle stress generated, the wide pull-up variant appears to focus on the back muscles to actuate the motion, with a higher proportion of muscle stress concentrated in trapezius, latissimus dorsi, and rhomboid major (Figure 3; $P < .01$) than front or reverse variants. Further, latissimus dorsi is relatively more engaged and supraspinatus appears relatively less so in the wide pull-up (Figure 2). The front pull-up favored activation of biceps brachii and brachialis more so than the other two pull-up variants ($P < .02$; Figure 2) indicating that elbow flexion may be a more central component. Muscle stresses in the reverse pull-up variant are comparatively higher overall, displaying early activation of pectoralis major (PM), with extensor function from triceps brachii and infraspinatus moving the humerus out of a flexed position. The reverse pull-up shows increasing contributions from deltoid (Delt) toward the end of motion and supraspinatus (Sup) through the mid-range, compared to the front and wide variants (Figure 2).

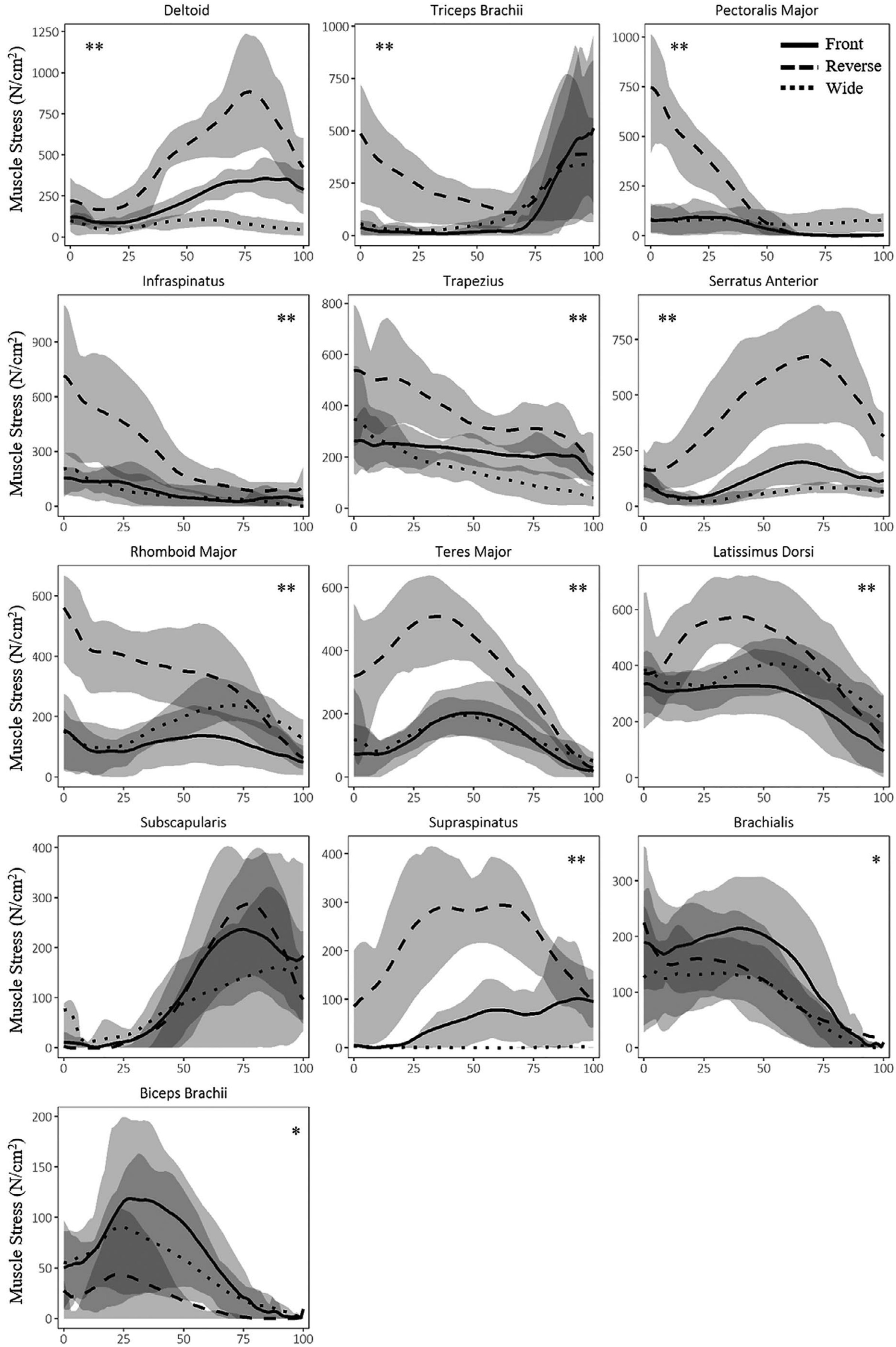

FIGURE 2 Muscle stresses (mean ± SD) during three pull-up variations for each of the largest force contributors, where maximum force for each muscle shown is greater than 10% body weight. *$P < .05$ and ** at $P < .01$ for repeated measures ANOVA across variants

3.2 | Mean muscle force

Force contributions are presented for each of the three pull-up variants for each muscle where average muscle force exceeded 10% of body weight (Figure 4). Mean force in the reverse pull-up was significantly higher than in wide and front pull-up variants for all muscles ($P < .001$) except subscapularis, brachialis, and triceps brachii, where no differences between methods were seen ($P = .67$; $P = .15$; $P = .07$), and biceps brachii, where reverse grip force was significantly lower than wide and front grip ($P < .005$).

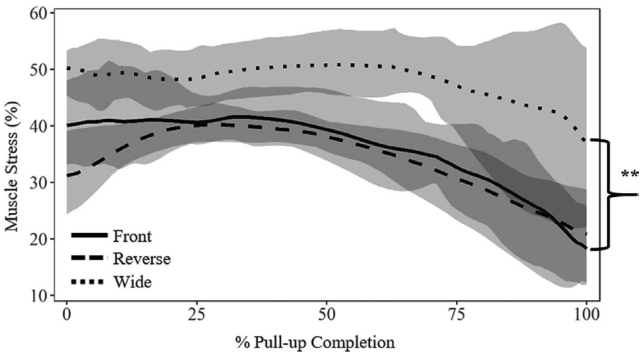

FIGURE 3 Percentage of muscle stress (mean ± SD) during three pull-up variations concentrated in key back muscles (trapezius, latissimus dorsi, and rhomboid major), compared to total muscle stress generated. Wide pull-up is significantly greater than front or reverse variants. $^{**}P < .01$

Rotator cuff stress was calculated as the sum of muscle stress from Sup, Inf, Sub, and teres minor (TMin) as a percentage of the summed stress of all the muscles crossing the glenohumeral joint (Delt, PM, LD, TMaj, Tri, Bic, Inf, Sup, Sub, TMin, coracobrachialis). The reverse pull-up showed the greatest proportion of muscle stress concentrated in the rotator cuff (30%), compared to the front (25%) and wide (20%) variants (Figure 5; $P < .05$ & $P < .01$). Individual rotator cuff muscle stress contributions show that subscapularis loading is consistent across variants and differences appear primarily related to changes in supraspinatus and infraspinatus loading (Figure 4).

3.3 | Maximum muscle force

Maximum force values highlight muscles that have peaks during a movement but may be less active overall, based on their mean muscle force (Figure 6). Triceps brachii has a significantly higher maximum muscle force in the reverse pull-up than in the wide variant ($P < .001$), which is also lower than in the front variant ($P < .01$). Maximum muscle forces in the reverse pull-up highlight peaks for infraspinatus and triceps brachii near the start of motion and supraspinatus in the mid-range of motion (Figure 2, $P < .001$). Pectoralis major had significantly higher peak activation during the reverse pull-up than during the front or wide pull-up (Figure 6; $P < .0003$), particularly for initiating movement (Figure 2),

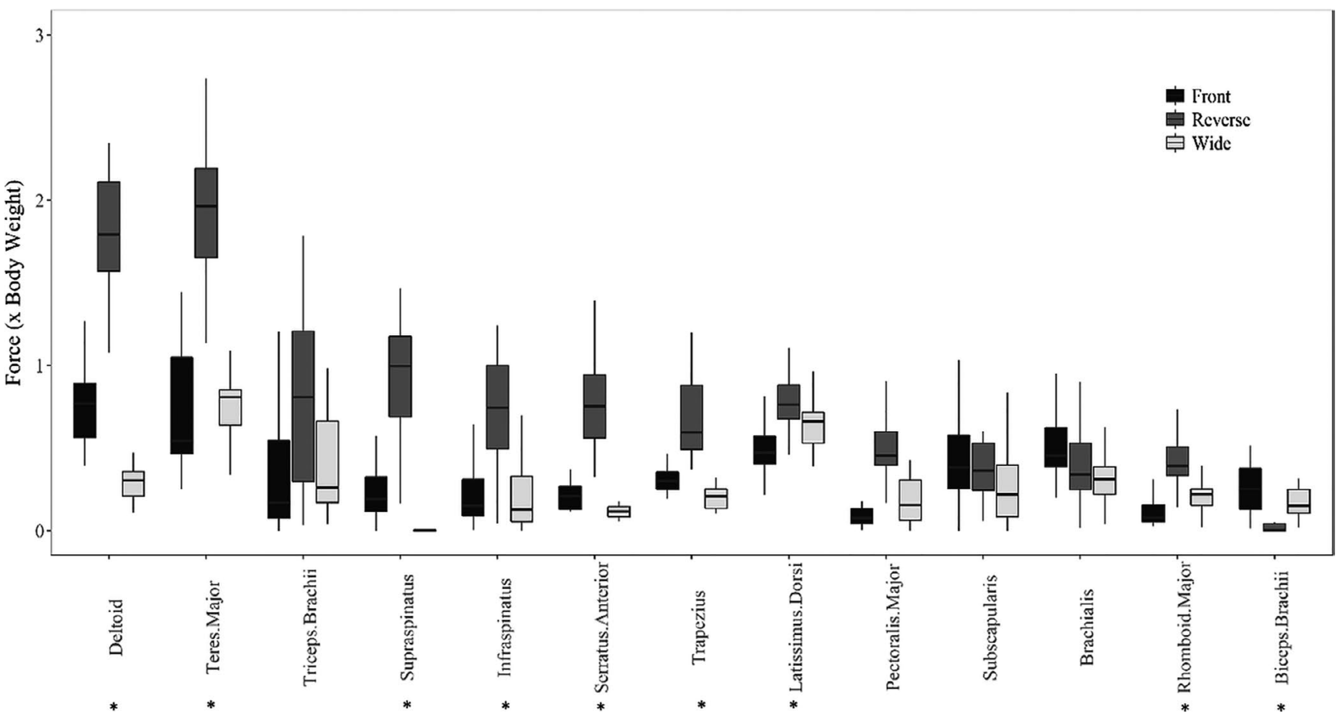

FIGURE 4 Box & whisker plots of mean individual muscle force contributions across each of three pull-up techniques from start of upward movement to end of upward movement. $^{*}P < .05$

as larger moments are required in extending and adducting the humerus during the reverse pull-up.[11]

4 | DISCUSSION

This study used experimentation and computational modeling to quantify loading of upper limb and torso muscles during three pull-up variants. The key muscles for actuating the pull-up activity show similarities across techniques, but differences exist in recruitment strategies. At the start of motion, when the humerus is at a high elevation angle, latissimus dorsi, posterior deltoid, and teres major act as prime actuators, depressing the upper arm and elevating the torso.

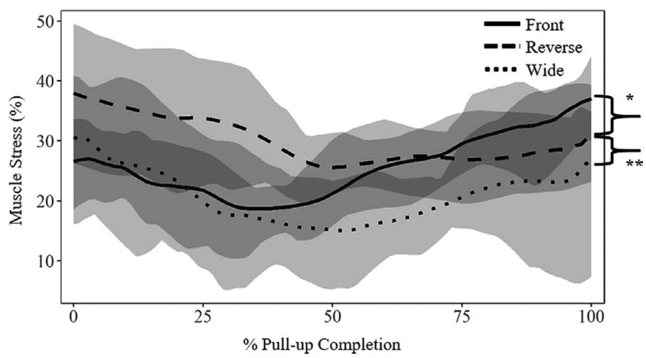

FIGURE 5 Summation of muscle stress concentrated in the rotator cuff muscles, as a percentage of the total stress generated by all the muscles crossing the glenohumeral joint during each pull-up variant. $^*P < .05$ and $^{**}P < .01$

Several other muscles contribute at points through the activity, including rhomboid major and trapezius which undergo large stresses while assisting in scapular positioning, and triceps brachii fully extending the humerus at the top of movement. The rotator cuff muscles—infraspinatus and subscapularis—act to constrain large forces at the glenohumeral joint at the bottom and top of motion, respectively. In the last 25% of upward motion, independent of variant ($P = .67$), subscapularis generates an internal rotation moment to the humerus.

To maintain scapular stability around the medial/lateral axis, rhomboid major, serratus anterior, and trapezius hold the medial border of the scapula close to the thorax.[29,30] Stability criteria for the UKNSM are such that if glenohumeral joint shear forces are directed outside the glenoid rim, a co-contraction mechanism is activated, which reflects the glenoid's proprioceptive role in stabilizing the shoulder joint, and contributes to reflexive contractions in the stabilizing muscles.[31] All the subjects in this study were pain and injury free, technically competent, un-fatigued, and therefore consistent. It would be reasonable that such a non-pathological state would be well reflected by the UKNSM joint stability constraints.

4.1 | Predicted muscle activation and EMG patterns

There has been one published musculoskeletal modeling study examining muscle and joint forces produced during

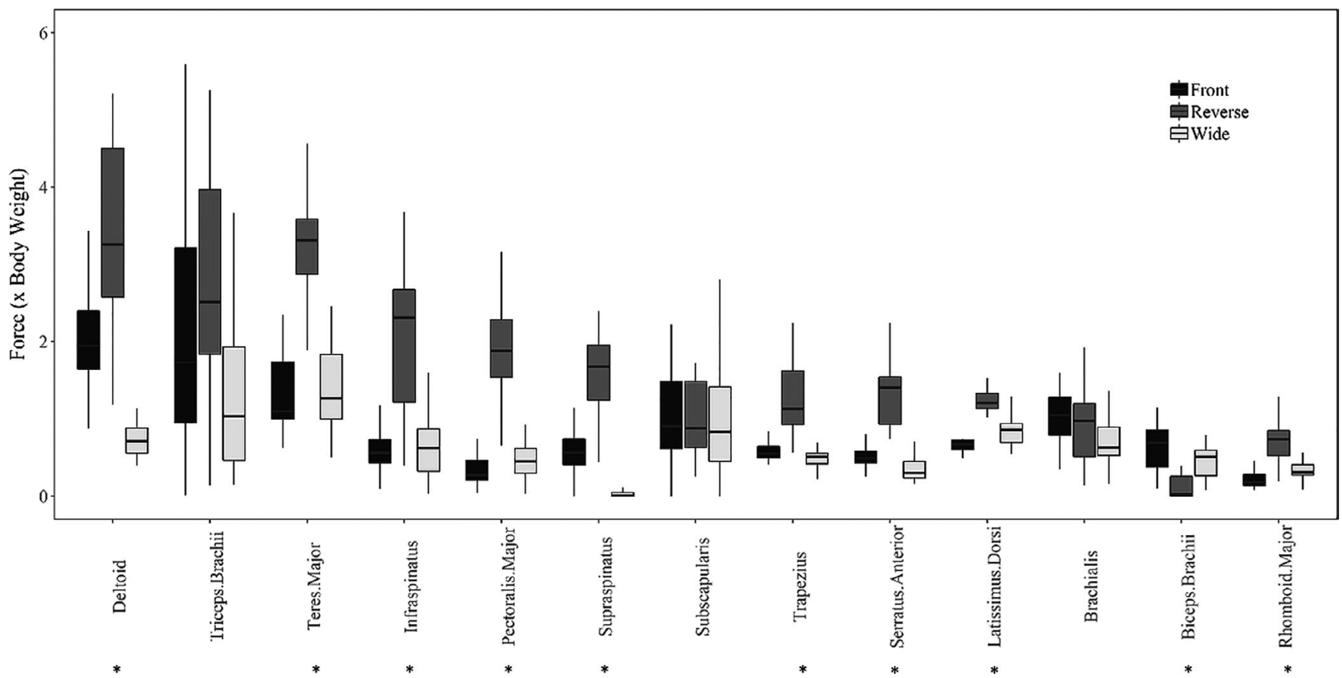

FIGURE 6 Box & whisker plots of maximum muscle force (mean ± SD) generated by individual muscles during each of three pull-up techniques from start of upward movement to end of upward movement. $^*P < .05$

reverse pull-ups and which included EMG verification.[17] Other studies have measured EMG during pull-up techniques with hand-grip variations and can be compared to model predictions of muscle force and recruitment predicted here.[4,14-16] Normalized, modeled muscle force values were on average lower than normalized EMG measurements from literature but have similar trends. EMG muscle activations reported by Dinunzio et al[15] for the front pull-up and Runciman[17] for the reverse pull-up indicate latissimus dorsi as the most active muscle during the pull-up movement, with pectoralis major appearing significantly less important. However, Doma et al[14] found activation for biceps brachii slightly larger than latissimus dorsi. The current data indicate increased muscle activity in the reverse pull-up for pectoralis major, serratus anterior, and supraspinatus, compared with the front and wide pull-ups. Brachialis and biceps brachii showed a comparative decrease in muscle activity in the reverse pull-up (Figure 4). While it is understood that supraspinatus initiates abduction, the pull-up activity is essentially loaded adduction, where supraspinatus acts in the mid-range to keep the humeral head compressed into the glenoid fossa.[32] Additionally, proprioceptive Type IV mechanoreceptors within the rotator cuff muscles and tendons may also act in anticipation of pending initiation of motion.[28,33]

In contrast to the results here, Youdas et al[4] found the reverse grip more effective at activating biceps brachii, compared to a front grip. The authors also found decreased muscle activity in trapezius and infraspinatus for the reverse grip, while latissimus dorsi remained unchanged. Runciman[17] found a high force contribution from subscapularis alone in the reverse grip. In the current study, while combined contribution of the rotator cuff muscles to the pull-up movement is larger in the reverse variant (Figure 4), the differences are attributed to infraspinatus and supraspinatus, not subscapularis (Figure 2). However, deviation from the literature in infraspinatus and triceps activation could result from differences in experimental protocol or experience of participants with pull-up tasks. While EMG measurements are useful in indicating the pattern of muscle activation, they should be treated with caution as they are also susceptible to cross-talk and are poor indicators of absolute muscle activation levels.[5,34]

4.2 | Injury risk in concentric and eccentric loading

It has been shown that eccentric loading and active muscle strain rate are key mechanisms of muscle damage and tendon injury.[28,35] Deltoid, triceps brachii, and supraspinatus are highly eccentrically loaded during pull-ups. Deltoid provides an abduction moment to the GH joint, improving joint stability at the top of the motion but at the bottom of motion, in eccentric loading, it pulls the humeral head superiorly along the glenoid, into a position of increased risk of subacromial impingement and it has been suggested that extrinsic compression may have an abrasive effect on tendons.[36,37]

Impingement injuries are possible when the subacromial space is at its smallest, at 120° humeral elevation, 90° abduction, and 45° external rotation.[38] This position corresponds approximately to 20%-60% of the pull-up motion, when supraspinatus is most active. When hand grip is closer together as in the front and reverse pull-ups, the required abduction moment is increased.[11] Fatigue could lead to increased eccentric loading on supraspinatus and higher risk of injury. Wide pull-ups avoid high stresses in both deltoid and supraspinatus, instead emphasizing the back muscles: latissimus dorsi, trapezius, and rhomboid major (Figure 3). When considering potential impingement risk, the supraspinatus force is not the only significant variable as scapular position will also influence impingement caused by external compression on the tendon. In the previous kinematic study, Prinold et al[11] suggest that the starting scapular position in the wide pull up technique may reduce sub-acromial space, contributing to increased pressure and thus a higher potential for impingement. Biceps brachii injuries and tendonitis at the elbow are commonly reported among climbers and gymnasts and have been associated with high stresses.[1,2] However, high biceps brachii stresses were not predicted in this study. This may reflect the role biceps short head and brachialis have in flexing the elbow, but the biarticular origin of biceps long head acts as a pull-up antagonist, opposing depression of the arm, and acting as a stabilizer.

4.3 | Implications for rehabilitation, strength and conditioning

Pull-ups utilize multiplanar motion and muscle co-contraction to promote stability of the shoulder and are regularly used as an upper-body strength metric and training tool. Understanding and implementing strength and conditioning principles is highly applicable when designing a rehabilitation program, particularly for athletes.[39] Rehabilitation strength training may focus on modifying scapula movement patterns and on balancing upper limb pressing and pulling performance to minimize risk of shoulder trauma.[39] This study clearly indicates that the mechanical demands placed upon the muscles of the shoulder and trunk can be modified simply by changing hand grip positions from narrow to wide, and orientations from pronated to supinated.

Results from the current study complement those from Prinold & Bull,[11] which showed that achievement of the same task can yield kinematic variances across subjects, suggesting that specific kinematic patterns may be responsible for potentially injurious poses where a different kinematic pattern would avoid such poses. As such, rehabilitation training may aim to preferentially teach a consistent muscle force pattern. Across all pull-up variants, elbow flexion is secondary to moving the humerus toward the trunk, but there are significant differences between the three pull-up variants in load-sharing, with the most marked difference between pronated-grip and supinated-grip orientations.

Reverse pull-ups display increased loading through the deltoid and rotator cuff muscles; therefore, it may be prudent to avoid them when managing deltoid or supraspinatus pathologies, instead utilizing a wide-grip variant, which emphasizes the back muscles. Conversely, a front pull-up variant may be ill-advised in biceps brachii or brachialis pathologies, as front pull-ups preferentially load those muscles (Figure 5). Pull-ups in general are a late-stage training exercise, but there are reasonable benefits to incorporation of exercises at some reduced percentage of the required force, such as lateral pull-downs or weight-assisted pull-ups to reproduce forces and loading rates that approach functional demands.[40] Isolated traumatic tears of the subscapularis are uncommon but more frequently subscapularis tenotomy is part of a surgical approach to the glenohumeral joint.[41] When rehabilitating post-operative patients in whom this has been performed, high levels of subscapularis loading in all three variants should be considered and pull-ups avoided until the tendon is fully healed.

4.4 | Limitations

When modeling musculoskeletal structures in complex activities, positions at high elevations and large external rotations may cause muscle lines to slide into non-physiological locations relative to the glenohumeral head. Via points were added to overcome this.[26] The UKNSM load-sharing algorithm was not constrained with an upper bound for muscle force because any amount of constraint prevented convergence of the model. While this is an idealized simulation, the result implies that the muscles in question are much stronger than the force limits for which standard modeling approaches have been previously optimized. While the UKNSM lacks the bones and musculature to model the hand, the effect of grip strength to proximal muscle recruitment is small relative to the overall force and activation predicted for pull-ups.[42]

Given experimental limitations of available equipment, it was assumed that force vectors at the hands were always perpendicular to the pull-up bar. Experiments in the literature using an instrumented pull-up bar have shown that the contribution of lateral forces is on average, only 0.06% of body weight, a small proportion of the total force generated[17]; however, use of an instrumented pull-up apparatus is recommended for future experiments on this type of activity.

5 | CONCLUSIONS

Pull-ups are an effective method of upper body strength training, promoting stability of the shoulder girdle and activation of scapula stabilizers. This study examined the effect of different kinematic strategies on muscle recruitment and highlighted potential injury risk in concentric loading of vulnerable structures, specifically the rotator cuff muscles, under complex and strenuous movement patterns involving high upper limb elevation. Results support the idea that torso elevation is the primary objective, with arm depression being a secondary event. However, there are significant differences between the three pull-up variants in movement pattern and muscle recruitment.

6 | PERSPECTIVES

To maximize the benefit of pull-ups, performing the task over its full range of motion is important as different portions of the task emphasize different muscles.[11] Given their heavy load and multi-planar complexity, pull-ups should be implemented as a late-stage component in shoulder rehabilitation and conditioning programs[5,39] and should encourage incorporation of all three pull-up variants with systematic progression to provide greater global strengthening of the torso and upper limb musculature. However, selection of the appropriate pull-up variant is important to complement the management of specific pathologies.

ACKNOWLEDGEMENTS
The work presented here is part of a Biotechnology and Biomedical Sciences Research Council (BBSRC) CASE studentship in conjunction with Vicon Motion Systems.

CONFLICTS OF INTEREST
The authors declare that no financial or personal relationships with people or organizations have inappropriately influenced this work and that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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How to cite this article: Urbanczyk CA, Prinold JAI, Reilly P, Bull AMJ. Avoiding high-risk rotator cuff loading: Muscle force during three pull-up techniques. *Scand J Med Sci Sports*. 2020;30:2205–2214. https://doi.org/10.1111/sms.13780