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Analysis of Muscle Activation Patterns during Mil-Zadan, Kabadeh-Keshi, and Sang-Gereftan Movements in Traditional Zurkhaneh Sports Using Electromyography and Motion Modeling in Elite Athletes: An Exploratory Case Study

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Original Article

Abstract

Introduction: Despite its high cultural value, Zurkhaneh sport is associated with a significant prevalence of upper extremity injuries. The lack of a reference pattern of muscle activity in elite athletes and the failure to utilize modern methods such as movement modeling represent a major research gap. This study aimed to analyze the muscle activity pattern in Mil-Zadan, Kabadeh-Keshi, and Sang-Gereftan movements using surface electromyography (sEMG) and biomechanical modeling to provide a reference pattern for rehabilitation and injury prevention.

Materials and Methods: In this analytical-descriptive study, two elite Zurkhaneh athletes (mean weight: 52 kg, height: 166 cm) were evaluated. Electromyographic (EMG) activity of six muscles (biceps, triceps, latissimus dorsi, middle deltoid, upper trapezius, and pectoralis major) was recorded during maximal voluntary contraction (MVC) and while performing the movements. Kinematic data were collected using a 10-camera motion analysis system (200 Hz) and link-segment modeling in Mokka software. EMG data were normalized to the MVC and reported as a percentage of maximal root mean square (RMS) activity.

Results: During Mil-Zadan, the biceps were activated before movement, and the triceps played an eccentric role in the overhead phase. In Kabadeh-Keshi, the middle deltoid showed the highest activity, followed by the latissimus dorsi and triceps. In Sang-Gereftan, the middle deltoid and triceps had the highest activity in controlling the weight of the stone. In all three movements, the biceps and triceps played a protective-control eccentric role.

Conclusion: The phased patterns of concentric and eccentric contractions in elite athletes showed that the elbow muscles played a key role in the eccentric control of torques. These findings can be used as a reference pattern for designing rehabilitation programs, eccentric strengthening, and preventing shoulder and elbow joint injuries in Zurkhaneh athletes.

Keywords: Biomechanical modeling; Muscle contraction; Resistance training; Shoulder girdle; Surface electromyography

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Introduction

Zurkhaneh sport is regarded as one of the oldest and richest training systems and holds a unique position in Iranian culture and sport. It comprises a series of complex and rhythmic movements performed using traditional implements such as the *Mil*, *Kabadeh*, and *Sang*. In addition to playing an important role in enhancing strength, endurance, and neuromuscular coordination, these movements require precise and coordinated use of the limbs in accordance with biomechanical principles (1, 2). In fact, one of the fundamental determinants of success in any sport is the proper use of the limbs and the optimal application of the physical laws governing movement; however, this cannot be adequately achieved without a thorough understanding of movement patterns and muscle activity (3). In this regard, biomechanics, through the analysis of movement and muscle function, provides an opportunity to identify optimal movement patterns and can contribute to improving technique, enhancing efficiency, and reducing unnecessary stress on musculoskeletal structures (4).

Despite the numerous benefits of this sport, evidence indicates that the prevalence of musculoskeletal injuries among Zurkhaneh athletes is considerable, with a substantial proportion of these injuries occurring in the upper extremities, particularly the shoulder joint and shoulder girdle (5, 6). The nature of movements in this sport, which involves repetitive activities, overhead movements, and the application of substantial forces, increases the mechanical load imposed on joints and soft tissues (6, 7). Epidemiological studies have reported a considerable incidence of injuries in this sport, with a substantial proportion associated with movements such as *Kabadeh-Keshi*, *Mil-Zadan*, and rotational movements (5). In this regard, some studies have shown that in several Zurkhaneh skills, including *Sang-Gereftan* and *Mil-Zadan*, the activity of the anterior shoulder-girdle muscles is predominant over that of the posterior muscles. This muscular imbalance may disrupt scapulohumeral rhythm and increase the risk of injury (6, 8).

Among previous studies, biomechanical investigations of these movements have largely been limited to descriptive or comparative analyses (9). For example, a study by Jafarnezhad et al. compared muscle activity during the *Sang-Gereftan* skill with that observed during the bench press exercise. The results demonstrated significant differences in muscle activation patterns between the two tasks, highlighting the distinctive characteristics of Zurkhaneh movements (9). However, such studies have generally been limited to a single movement or comparisons with conventional resistance-training exercises, with relatively little attention given to the simultaneous investigation of multiple key skills in this sport. Furthermore, many of these studies have not employed advanced approaches, such as musculoskeletal modeling, to provide a more in-depth interpretation of the data; instead, their analyses have primarily relied on raw electromyographic data or observational assessments of movement (3, 10).

Another important gap in the existing literature is the absence of a reference profile of muscle activity in elite athletes. Most previous studies have either been conducted in non-professional populations or have examined a limited number of muscles, without adequately addressing the complex interactions among muscles as an integrated system (6, 10). In addition, the direct relationship between biomechanical findings and rehabilitation and injury-prevention applications has not been clearly established in many studies, limiting the practical applicability of their findings for coaches and sports professionals (11).

In recent years, advances in measurement and motion-analysis technologies, particularly surface electromyography and biomechanical modeling, have enabled the quantitative assessment of joint angles, muscle function, and their interactions during the execution of athletic movements (10, 12). Integrating these methods can provide deeper insight into muscle activation patterns, force distribution, and the role of individual muscles in controlling and generating movement (3, 12). Nevertheless, the simultaneous application of these two approaches to the analysis of Zurkhaneh movements has rarely been investigated, representing an important gap in the existing literature.

From a rehabilitation perspective, establishing accurate muscle-activity profiles in healthy, highly trained athletes plays a critical role in designing rehabilitation programs, correcting muscular imbalances, and retraining movement patterns (1, 11). The absence of such reference profiles limits the assessment and treatment of injured athletes, resulting in clinical decisions that may rely more heavily on individual experience than on scientific evidence. Furthermore, identifying aberrant muscle-activation patterns may serve as a tool for injury prediction and early intervention, thereby helping to prevent the progression of musculoskeletal injuries (7, 11). Accordingly, integrating precise biomechanical analysis with rehabilitation applications may play an important role in promoting athletes' health and performance.

Despite the considerable importance of biomechanical analysis of Zurkhaneh movements, studies based on electromyography and motion

modeling in elite athletes in this discipline remain very limited. Moreover, access to professional Zurkhaneh athletes who are capable of performing standardized movements while simultaneously undergoing electromyographic recording and three-dimensional motion analysis is associated with practical and technical limitations. The complexity of the measurement protocol, the time required for participant preparation, and the difficulty of simultaneously recording kinematic and electromyographic data also limit the feasibility of conducting studies with large sample sizes during the initial phase of research. Therefore, the present study was designed as an exploratory case study to initially identify muscle-activation patterns and motor-control characteristics in elite athletes and to provide a foundation for future studies with larger sample sizes.

Given the limitations of previous studies and the absence of a reference profile of muscle activity in elite Zurkhaneh athletes, research employing advanced motion-analysis methods is warranted. Accordingly, the present study was designed as an exploratory case study to investigate the upper-extremity muscle-activation patterns during three fundamental Zurkhaneh movements—*Mil-Zadan*, *Kabadeh-Keshi*, and *Sang-Gereftan*—in elite Zurkhaneh athletes using surface electromyography and biomechanical motion modeling. The primary aim of this study was to analyze muscle-activation patterns and their relationship with the biomechanical control of the shoulder and elbow joints, with the ultimate goal of establishing an initial reference profile for rehabilitation applications, the design of sport-specific training programs, and injury prevention in Zurkhaneh sport.

Materials and Methods

The present study was a descriptive–analytical exploratory case study conducted to investigate upper-extremity muscle activation patterns during selected Zurkhaneh movements. Simultaneous recordings of surface electromyographic (sEMG) data and three-dimensional movement kinematics were obtained from elite Zurkhaneh athletes, and the association between muscle activity and changes in joint angles was analyzed. Given the exploratory nature of the study, the complexity of the data-acquisition protocol, and the limited access to eligible professional athletes, the study was conducted as a case study involving two elite athletes to identify preliminary patterns of muscle activation and motor control during these movements.

Prior to data collection, the participants were asked to perform a standardized 10-minute warm-up protocol. This protocol consisted of 5 minutes of light aerobic activity (walking and rhythmic upper-extremity movements), 3 minutes of dynamic stretching exercises targeting the shoulder-girdle and upper-extremity muscles, and 2 minutes of low-intensity practice of specific Zurkhaneh movements. The purpose of the warm-up was to increase muscle temperature, prepare the neuromuscular system, and reduce the risk of injury during the testing procedures.

Surface electromyographic activity was recorded from the biceps brachii, triceps brachii, latissimus dorsi, middle deltoid, upper trapezius, and pectoralis major muscles using a wireless surface electromyography system (Mega ME6000; Megar Electronics Ltd., Kuopio, Finland). The system operated at a sampling frequency of 2000 Hz, with a common-mode rejection ratio (CMRR) of >100 dB and a band-pass filter of 20–500 Hz.

For this purpose, the participants' skin was first prepared according to the European SENIAM protocol guidelines (13, 14). Excess hair at the electrode sites was removed using a disposable razor, and the skin surface was then cleaned with alcohol to reduce skin resistance, dead skin cells, and noise associated with skin impedance. The precise location of each muscle was identified by palpation of anatomical landmarks and isometric contraction to locate the muscle belly (15).

Muscle activity was recorded using bipolar Ag/AgCl surface electrodes. The electrodes were placed longitudinally along the muscle fibers and over the muscle belly, with an inter-electrode center-to-center distance of 20 mm. Electrode placement was determined according to SENIAM recommendations. Specifically, the electrodes for the biceps brachii were placed at the midpoint between the cubital fossa and the acromion process; for the triceps brachii, at the midpoint of the posterior aspect of the upper arm; for the middle deltoid, midway between the acromion and the deltoid tuberosity; for the upper trapezius, halfway between the C7 vertebra and the acromion; for the latissimus dorsi, along the muscle fibers in the posterolateral region of the trunk; and for the pectoralis major, at the midpoint between the sternum and the anterior axillary fold.

A reference/ground electrode was placed over the olecranon process of the elbow to minimize environmental electrical noise. To prevent electrode displacement and reduce motion artifacts, the electrodes were secured using specialized double-sided adhesive tape and medical adhesive tape.

Before recording the main experimental data, the activity of each of the aforementioned muscles was recorded during a maximum voluntary isometric

contraction (MVC) (Figure 1A). For MVC assessment, each muscle contraction was maintained for 10 seconds. The MVC data were used to normalize muscle activity during the performance of the experimental tasks. Three MVC trials were recorded for each muscle, and the mean value of the three trials was used for normalization of muscle electrical activity (16).

Kinematic data were collected using a 10-camera motion-analysis system (Motion Analysis, USA) operating at a sampling frequency of 200 Hz, together with reflective markers, marker clusters, and double-sided adhesive tape. The motion-analysis cameras recorded the three-dimensional spatial positions of each marker during a specific movement or posture at a given time point. These three-dimensional marker positions were determined relative to a reference coordinate system predefined by the motion-analysis laboratory operator within the software. To improve measurement accuracy and minimize marker displacement, the markers were attached to bony anatomical landmarks (17), as these structures exhibit less movement relative to the surrounding soft tissues, allowing the rigid-body assumption to be applied more accurately. Inverse kinematic analysis was used to calculate the elbow joint flexion angle from the positions of the upper-extremity markers (18).

Following MVC recording, the participants were instructed to perform the *Mil-Zadan* movement (Figure 1B) and the *Kabadeh* movement (Figure 1C) continuously for 30 seconds. They then performed the *Sang* movement (Figure 1D) for 10 consecutive repetitions. Each of the aforementioned movement tasks was performed in three trials.

Muscle Signal Processing

To enable comparison of the electromyographic data, the signals recorded from each muscle during the performance of the athletic movements were normalized to the MVC value of the corresponding muscle. EMG signals were recorded at a sampling frequency of 2000 Hz.

To reduce noise and minimize cross-talk from adjacent muscles, the electrodes were placed according to the SENIAM guidelines over the muscle belly, aligned with the direction of the muscle fibers, with an inter-electrode distance of 20 mm. Efforts were also made to position the electrodes as far as possible from adjacent muscles. The use of bipolar electrodes and appropriate skin preparation further contributed to noise reduction and improved signal quality.

To minimize motion artifacts and noise associated with cardiac activity, the cables and transmitters of the wireless system were securely fixed. Following data acquisition, the signals were processed using a band-pass filter with a frequency range of 20–500 Hz and a Butterworth low-pass filter with a cutoff frequency of 20 Hz. In addition, the signals were visually inspected to identify and exclude data containing abnormal noise.

The root mean square (RMS) values were extracted from the filtered MVC signals using a 200-ms moving window. Maximum muscle activity was defined as the highest RMS value obtained during the MVC trials and was used as the reference value for normalization (14, 16).

To determine the onset and termination of muscle activity, the signals were first full-wave rectified and subsequently processed using a Butterworth low-pass filter to smooth the signals (19).

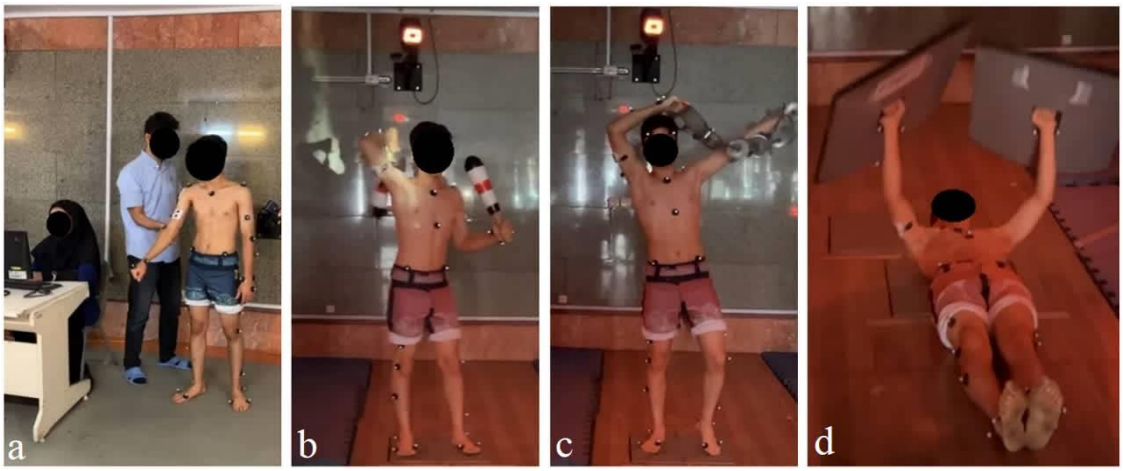


Figure 1. Motion analysis using cameras and markers and simultaneous recording of electromyographic signals: (A) biceps brachii MVC test; (B) motion analysis of the Mil-Zadan movement; (C) motion analysis of the Kabadeh-Keshi movement; and (D) motion analysis of the Sang-Gereftan movement.

At the beginning of each trial, several seconds of resting-state data were recorded, and the mean and standard deviation of this baseline period were used to determine the muscle-activity threshold. The point at which the signal amplitude exceeded the predefined threshold was considered the onset of muscle activity. Subsequently, the RMS of the signals was calculated over the period of muscle activity and expressed as a percentage of MVC (%MVC).

Biomechanical Motion Modeling

The marker trajectories and electromyographic signals recorded from the muscles were imported into Mokka software for biomechanical motion modeling. The markers were connected to define the body segments, and a joint-based link-segment model of the human body was constructed for the aforementioned movements. Inverse kinematic analysis was then used to calculate the elbow joint flexion angles, allowing the relationship between joint angle and muscle activity patterns to be subsequently investigated from a biomechanical perspective (Figure 2).

The processing of the upper-extremity muscle signals described above included signal baseline correction, full-wave rectification, noise removal, low-pass filtering, and calculation of the root mean square (RMS) value. These processing steps were performed to extract the relevant muscle-activity data from the recorded signals (18, 20).

Results

The present descriptive–analytical study was conducted on two professional Zurkhaneh athletes, with a mean body weight of 52 kg and a mean height of 166 cm. The results of muscle activation during the *Mil-Zadan* movement showed that, prior to the initiation of the movement, the elite Zurkhaneh athletes controlled the weight of the *Mil* and the force of gravity primarily through the biceps brachii and upper trapezius muscles. Accordingly, these muscles were activated at the initial phase of the movement and contributed to raising the arm and flexing the elbow. Subsequently, the latissimus dorsi and middle deltoid contributed to further elevation of the *Mil*.

During the phase in which the *Mil* was held in the elevated position, the triceps brachii played an important role. During the return phase, particularly during horizontal adduction of the arm, the latissimus dorsi was predominantly involved. At the same time, the biceps brachii also contributed to controlling the movement and returning the arm to the starting position (Figure 3).

In the *Kabadeh-Keshi* movement, the latissimus dorsi and triceps brachii initially exhibited the highest levels of activity, respectively, contributing to movement control and maintaining the *Kabadeh* in an overhead position. Subsequently, the middle deltoid and upper trapezius were activated. The highest level of muscle activity during the *Kabadeh-Keshi* movement was observed in the middle deltoid, indicating that this muscle plays a primary role in performing this skill among Zurkhaneh athletes. The latissimus dorsi and triceps brachii demonstrated the next highest levels of activity.

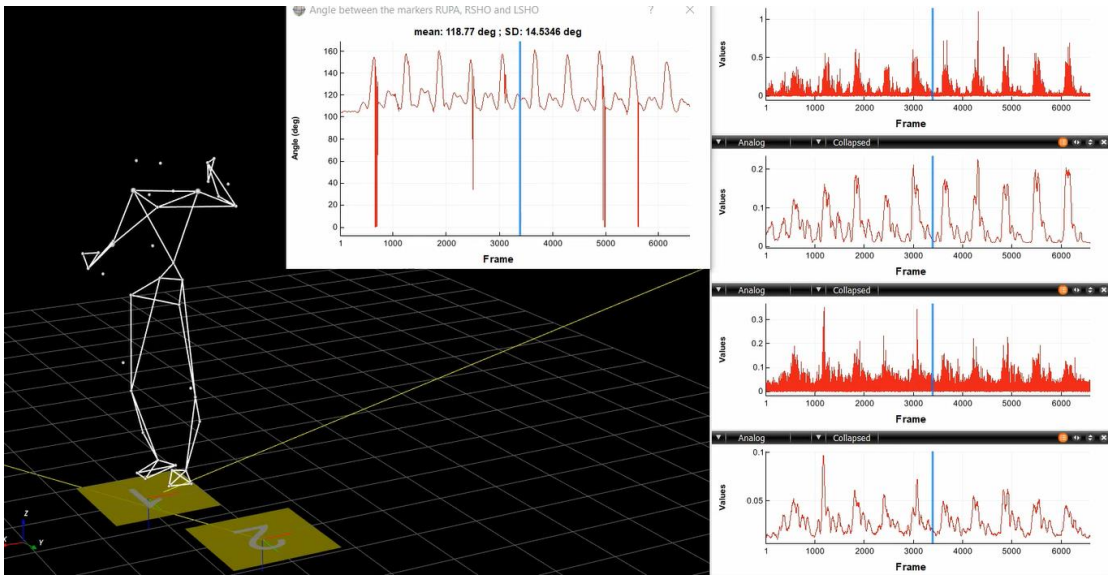


Figure 2. Joint-based link-segment biomechanical modeling of the human body in Mokka software, illustrating the changes in joint angles and muscle activity patterns.

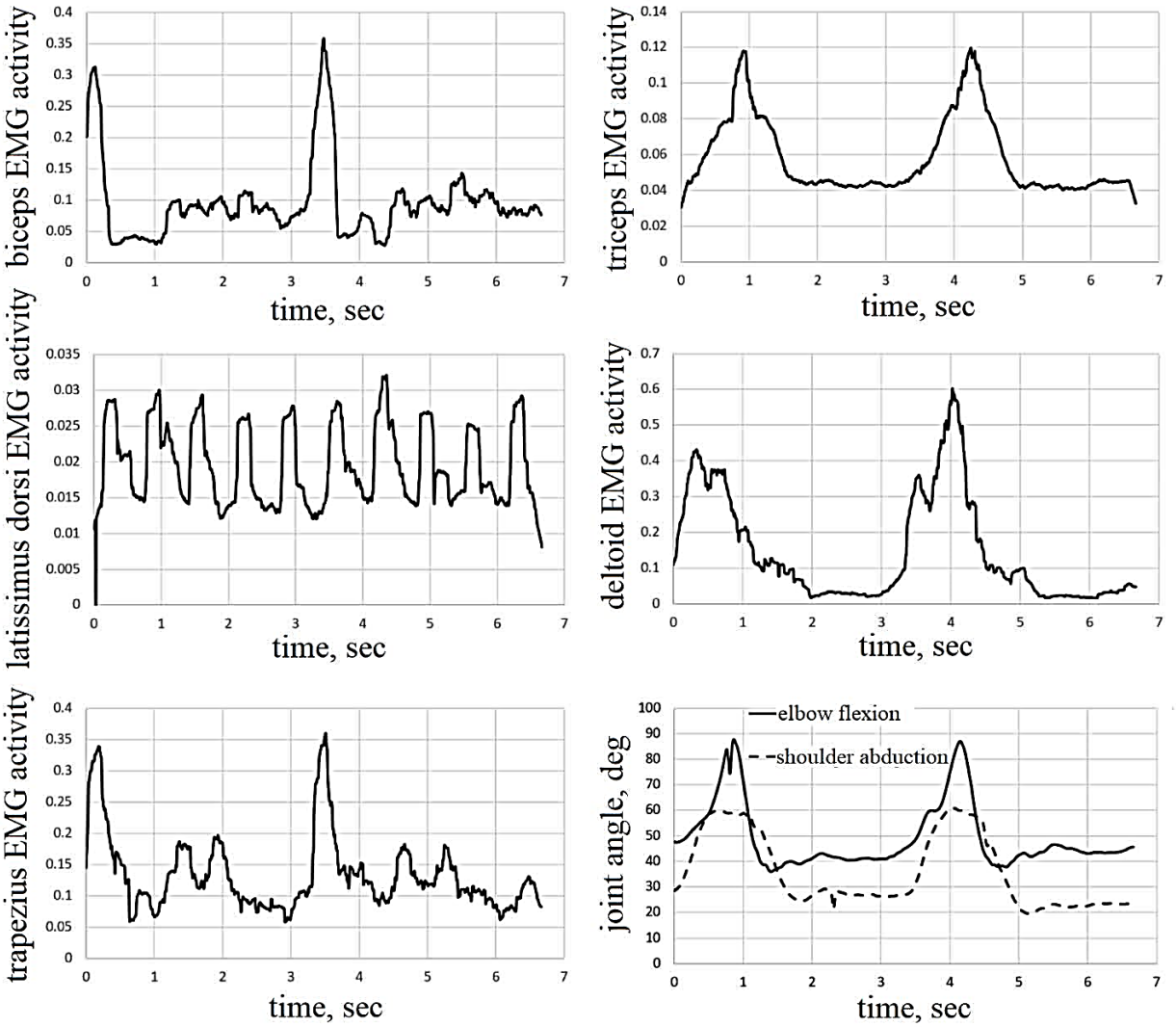


Figure 3. Normalized activity of the upper-extremity muscles, including the biceps brachii, triceps brachii, latissimus dorsi, deltoid, and trapezius, together with elbow flexion and shoulder abduction angles, plotted as a function of time during two cycles of the *Mil-Zadan* movement.

Since the *Kabadeh-Keshi* movement primarily involves shoulder abduction and adduction as well as elbow flexion and extension, the functional contribution of these two muscles to the execution of the movement is evident. The biceps brachii and triceps brachii also appear to play a predominantly stabilizing and protective role during this movement, potentially contributing to the prevention of musculoskeletal injury (Figure 4).

During the initial phase of the Sang movement, the triceps brachii and deltoid muscles exhibit the highest levels of muscle activity, indicating that these two muscles primarily control the weight of the Sang at this stage. Shortly after the onset of the movement, the pectoralis major also contributes substantially to counteracting the weight of the Sang and demonstrates considerable activity.

Throughout the movement, the deltoid and biceps brachii muscles serve supportive roles and contribute to movement control.

Discussion

The aim of the present study was to analyze the upper-limb muscle activation patterns during three fundamental movements in Zurkhaneh sport—Mil Zadan, Kabadeh pulling, and Sang grasping—using surface electromyography (sEMG) and musculoskeletal biomechanical modeling.

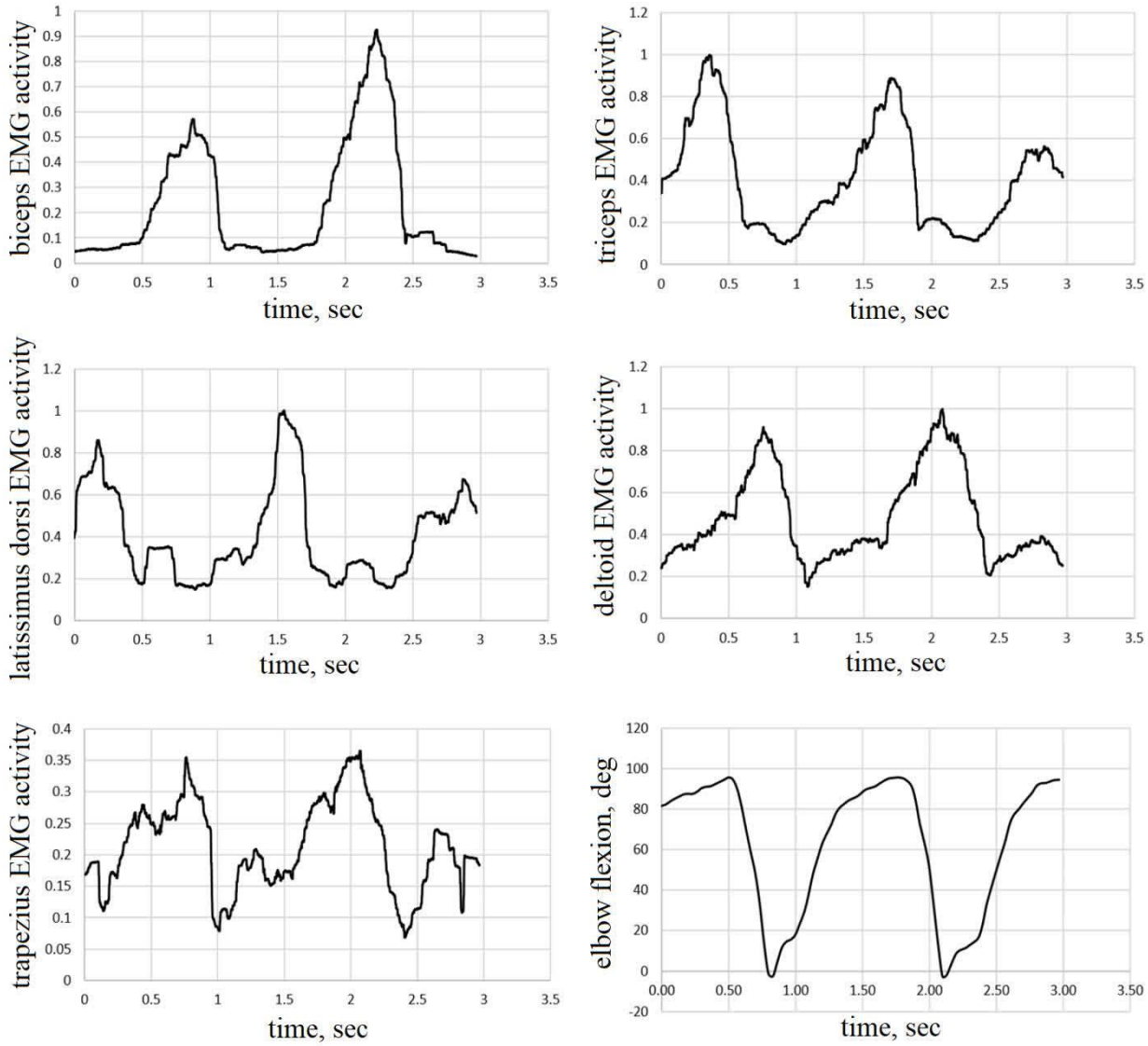


Figure 4. Normalized activity of the upper-limb muscles, including the biceps brachii, triceps brachii, latissimus dorsi, deltoid, and trapezius, along with elbow flexion angle as a function of time over two cycles of the Kabadeh movement.

The findings demonstrated that each movement exhibited a distinct pattern of muscle activation. However, across all three movements, the shoulder girdle muscles and the muscles controlling the elbow joint played key roles in load management, joint stabilization, and movement guidance.

During the Mil Zadan movement, early activation of the biceps brachii and upper trapezius was observed before the onset of movement, suggesting a neuromuscular pre-activation strategy to overcome the inertia of the implement and establish initial stability of the shoulder girdle. During the Kabadeh movement, the highest levels of muscle activity were observed in the middle deltoid, latissimus dorsi, and triceps brachii, whereas the biceps brachii and triceps brachii primarily contributed to movement control and joint protection. During the Sang-grasping movement, the triceps brachii, deltoid, and pectoralis major demonstrated the greatest contributions to controlling the weight of the Sang and guiding the movement. Furthermore, simultaneous analysis of EMG data and joint kinematics demonstrated that changes in muscle activity were closely associated with changes in elbow angle and shoulder position.

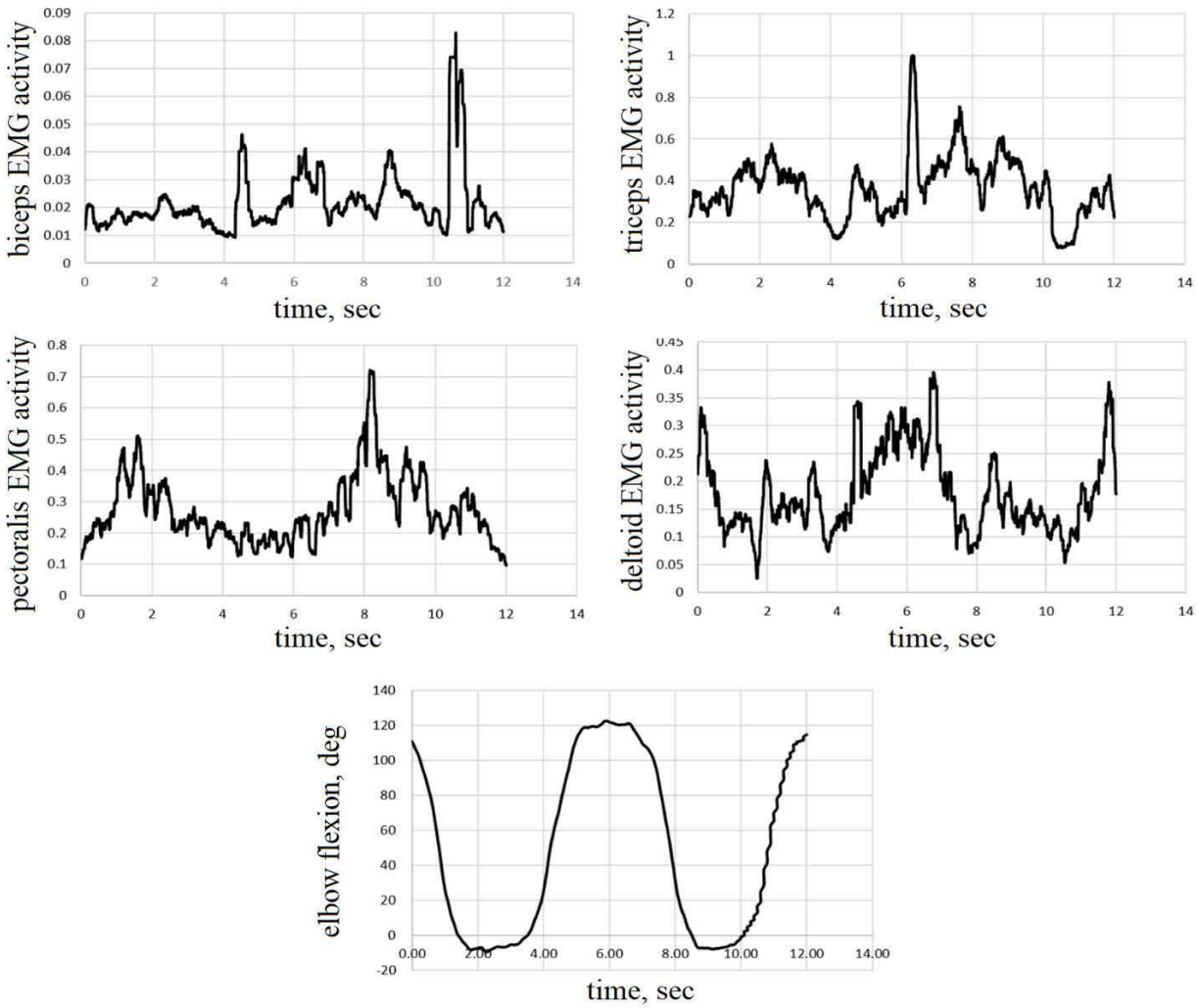


Figure 5. Normalized activity of the upper-limb muscles, including the biceps brachii, triceps brachii, pectoralis major, and deltoid, along with elbow flexion angle as a function of time during the Sang-grasping movement.

Depending on the type and direction of the joint moments acting during different phases of the movement, the muscles were activated through either concentric or eccentric contractions.

The findings of the present study are broadly consistent with previous research on the biomechanics of Zurkhaneh movements and overhead activities. Jafarnezhad et al. (9), in a comparison of the Sang-grasping movement and the bench press, reported that muscle activation patterns during Zurkhaneh movements differ from those observed during conventional resistance exercises and that the shoulder-girdle stabilizing muscles play a more prominent role in Zurkhaneh activities. The findings of the present study further support this observation, as considerable deltoid activity was observed during the Sang-grasping movement in addition to the activity of force-producing muscles such as the pectoralis major and triceps brachii. This finding suggests a greater demand for dynamic control and shoulder-joint stability during this movement. The potential differences between these findings and those observed during traditional strength exercises may be attributable to the multi-joint nature of Zurkhaneh movements, their curved movement trajectories, and the requirement to control free-moving implements.

During the Mil Zadan movement, the early activation of the biceps brachii and upper trapezius before movement onset suggests a neuromuscular strategy aimed at stabilizing the shoulder girdle and controlling the inertia of the implement.

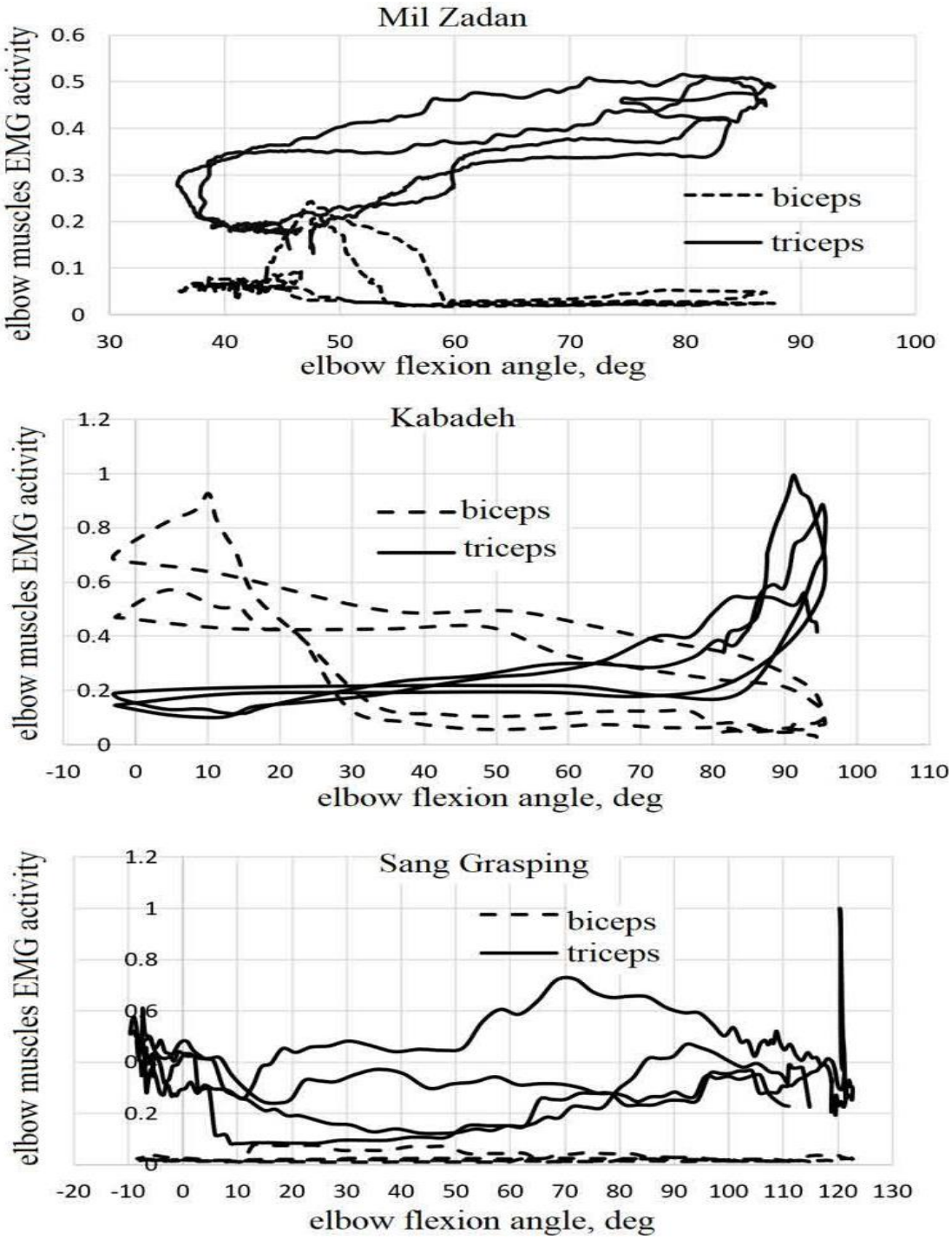


Figure 6. Normalized activity of the muscles acting on the elbow joint (biceps brachii and triceps brachii) as a function of elbow flexion angle during two cycles of three movements: Mil Zadan, Kabadeh, and Sang Grasping.

This finding is consistent with studies investigating overhead movement control and shoulder-girdle muscle activity, which have reported that pre-activation of the shoulder and scapular stabilizers during overhead activities is essential for reducing joint loading and maintaining scapulohumeral rhythm (6, 20). In addition,

the present findings showed that middle deltoid and latissimus dorsi activity increased with increasing shoulder abduction. This finding is consistent with biomechanical studies of shoulder abduction and flexion, in which the middle deltoid has been identified as a primary contributor to abduction torque generation. In contrast, the latissimus dorsi contributes to movement control and joint stabilization (3, 4).

In the present study, triceps brachii activity reached its highest level during the phase in which the Mil was held behind the head. This finding may be attributed to the role of the triceps brachii in controlling the flexion moment generated by the weight of the implement and gravitational forces. Previous studies of resistance and overhead activities have also demonstrated that the elbow extensors play an important role in eccentric movement control and in protecting the elbow joint under high external loads (7, 18). Conversely, the reduced activity of the biceps brachii while the Mil was positioned behind the head suggests that, during this phase, the flexion moment generated by the weight of the implement may partially reduce the need for active biceps recruitment. This finding may indicate that elite athletes efficiently exploit mechanical forces and minimize muscular energy expenditure during the movement.

Analysis of the Kabadeh movement showed that the middle deltoid exhibited the highest level of muscle activity, followed by the latissimus dorsi and triceps brachii. This finding is consistent with the biomechanical characteristics of the Kabadeh movement, which primarily involves shoulder abduction and elbow extension under substantial external loading. Previous studies have also shown that during overhead activities involving high external loads, the deltoid and trapezius muscles play essential roles in maintaining shoulder stability and preventing disruption of scapulohumeral rhythm (5, 6). In the present study, the simultaneous activation of the middle deltoid and upper trapezius was likely necessary to maintain scapular positioning and prevent excessive displacement of the humeral head.

Limitations

Given the exploratory and semi-experimental nature of this study, as well as the difficulty of recruiting elite Zurkhaneh athletes willing to participate in complex EMG and motion-analysis protocols, the sample was limited to two athletes. This limitation restricts the generalizability of the findings, and the results should therefore be interpreted as preliminary findings.

Another limitation was the inability to record the activity of deep muscles. Because surface electromyography was used, it was not possible to directly assess the activity of the deep shoulder rotator muscles, such as the supraspinatus and infraspinatus. These muscles play an important role in dynamic stabilization of the shoulder joint.

Recommendations

Future studies involving larger sample sizes, preferably 20–30 elite athletes, could provide a more robust reference pattern and enable the application of inferential statistical analyses. Simultaneous assessment of the rotator cuff muscles using fine-wire electrodes would provide a more comprehensive understanding of the mechanisms underlying shoulder-joint stabilization during overhead movements.

It is also recommended that future studies combine EMG and motion analysis with force-plate measurements and isokinetic dynamometry. Such an integrated approach would allow net joint moments to be quantified and directly compared with muscle activation patterns.

Longitudinal studies are also warranted to investigate the potential association between eccentric muscle-control deficits, particularly in the biceps brachii and triceps brachii, and the subsequent development of musculoskeletal injuries. A longitudinal cohort study following Zurkhaneh athletes for one to two years could provide valuable insight into whether specific muscle activation patterns are associated with future injury risk.

Furthermore, based on the muscle activation patterns identified in the present study, the development and evaluation of eccentric training protocols targeting the elbow and shoulder-girdle muscles through randomized controlled trials would represent a logical next step toward translating biomechanical findings into practical clinical and training applications.

Conclusion

Taken together, the EMG and musculoskeletal analysis findings indicate that muscle activation patterns during Mil Zadan, Kabadeh pulling, and Sang grasping in elite athletes reflect a highly coordinated motor-control strategy characterized by precise sequencing of concentric and eccentric muscle contractions and targeted involvement of the shoulder-girdle and elbow muscles. Muscles such as the middle deltoid and latissimus dorsi appear to play dominant roles in movement production, whereas the biceps brachii and triceps brachii contribute substantially to the eccentric control of moments generated by the weight of the implements.

From a biomechanical perspective, this activation pattern highlights the importance of maintaining an appropriate balance between agonist and antagonist muscle activity, as well as preserving scapulohumeral coordination during overhead movements. Disruption of this balance may increase mechanical stress on the shoulder joint and potentially contribute to the development of common shoulder injuries. From a rehabilitation perspective, these findings emphasize the need for movement-retraining programs that incorporate selective strengthening of stabilizing muscles, particularly during eccentric phases, together with correction of muscular imbalances.

With regard to injury prevention, emphasis on eccentric strengthening of the biceps brachii and triceps brachii at the elbow joint, along with improved neuromuscular control during transitional phases of movement, may play an important role in reducing the risk of injuries associated with repetitive loading and rapid movements. From a performance perspective, incorporating these reference activation patterns into the design of sport-specific and phase-based training programs may help optimize movement efficiency, reduce unnecessary energy expenditure, and improve skill execution in Zurkhaneh athletes.

Furthermore, the findings demonstrate that Zurkhaneh movements are characterized by coordinated and phase-specific muscle activation patterns, in which the balance between force-producing and movement-controlling muscles is critical for proper execution. Emphasizing eccentric strengthening of the elbow muscles and improving shoulder-girdle control may contribute to injury prevention. Incorporating these activation patterns into sport-specific training programs may also enhance athletic performance and movement efficiency.

The identified patterns of muscle contraction and muscle recruitment across different phases of the movements can provide valuable information for coaches in designing sport-specific training protocols. In particular, these findings may enable coaches to identify athletes' strengths and weaknesses at different phases of each movement and prescribe targeted training programs according to the muscles involved in each phase. Based on the musculoskeletal analysis of these movements, it may be recommended that coaches incorporate both eccentric and concentric training protocols targeting the elbow joint.

From a rehabilitation perspective, the activation patterns identified in the present study may serve as functional reference patterns for the development of movement-retraining programs. Emphasizing strengthening during eccentric phases, particularly for the biceps brachii and triceps brachii, together with improving neuromuscular control of the shoulder-girdle muscles, may help correct dysfunctional movement patterns and facilitate a safe return to training among injured athletes. Moreover, identifying the precise timing of muscle activation may facilitate the development of targeted exercises aimed at restoring intermuscular coordination.

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Project design and ideation: Neda Boroushak
Providing financial resources for the Project: Neda Boroushak
Scientific and executive support of the Project: Neda Boroushak
Providing equipmentsand statistical sample: Neda Boroushak, Mohammad Amin Mohammadian
Data collection: Neda Boroushak, Mohammad Amin Mohammadian
Analysis and interpretation of the results: Neda Boroushak, Rasoul Abedi
Specialized statistics services: Neda Boroushak, Rasoul Abedi
Manuscript preparation Neda Boroushak, Rasoul Abedi
Specialized scientific evaluation of the manuscript: Neda Boroushak, Rasoul Abedi
Confirm the final manuscript to be submitted to the journal: Neda Boroushak, Rasoul Abedi, Mohammad Amin Mohammadian
Maintaining the integrity of the study process from the beginning to the publication, and responding to the reviewer's comments: Neda Boroushak, Rasoul Abedi, Mohammad Amin Mohammadian

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Conflict of Interest

The authors did not have a conflict of interest.

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