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ORIGINAL ARTICLE

Comparative analysis of the maximum voluntary isometric contraction of the biceps brachii and triceps brachii at different elbow angles

Farklı dirsek açılarında biceps brachii ve triceps brachii kaslarının maksimum istemli izometrik kasılmasının karşılaştırmalı analizi

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Abstract

Purpose: The objective of this study is to compare the maximum voluntary isometric contraction (MVIC) values obtained from the biceps brachii (BB) and triceps brachii (TB) muscles at different elbow angles and to determine which angle provides optimum efficiency according to this comparison.
Methods: A total of 30 healthy volunteers participated in the study. Electromyography (EMG) data were obtained at 70°, 90°, and 110° of flexion to measure root mean square (RMS) amplitude during MVIC of BB (for elbow flexion) and TB (for elbow extension) muscles.
Results: For BB, EMG RMS amplitude during MVIC was significantly influenced by elbow joint angle, with the highest activation observed at 70° compared to 90° and 110°. Similarly, TB activation was angle-dependent, showing the greatest values at 70°. The BB/TB EMG RMS ratio further confirmed consistently greater activation of BB across all joint angles. Post-hoc analyses revealed that BB activation was significantly greater at 70° compared with 90° and 110°, while TB activation was higher at 70° compared with 90° and 110°, and also higher at 90° compared with 110°.
Conclusion: The findings demonstrated that joint angle influences EMG amplitudes during MVIC for both BB and TB muscles. These findings highlight the importance of joint angle selection in exercise prescription and rehabilitation.
Keywords: Electromyography, Elbow joint, Biceps brachii, Triceps brachii, Isometric contraction.

Öz

Amaç: *Bu çalışmanın amacı, farklı dirsek açılarında biseps brachii (BB) ve triceps brachii (TB) kaslarından elde edilen maksimum istemli izometrik kasılma (MVIC) değerlerini karşılaştırmak ve bu karşılaştırmaya göre hangi açının en optimal verimliliği sağladığını belirlemektir.*
Yöntem: *Çalışmaya toplam 30 sağlıklı gönüllü katıldı. BB (dirsek fleksiyonu) ve TB (dirsek ekstansiyonu) kaslarının MVIC sırasında elektromiyografi (EMG) kök ortalama kare (RMS) genliği değerlerini ölçmek için 70°, 90° ve 110° fleksiyon açılarında EMG verileri elde edildi.*
Bulgular: *BB kasında MVIC sırasında EMG RMS genliği dirsek eklem açısına anlamlı şekilde bağlı bulunmuş olup, en yüksek aktivasyon 70°'de gözlendi. Benzer şekilde TB kasında da en yüksek aktivasyon 70°'de kaydedildi. BB/TB EMG RMS oranı, tüm açılarda BB'nin daha yüksek aktivasyon gösterdiğini ortaya koydu. Post-hoc analizlerde BB aktivasyonunun 70°'de 90° ve 110°'ye kıyasla anlamlı olarak daha yüksek olduğu, TB aktivasyonunun ise 70°'de 90° ve 110°'a göre, ayrıca 90°'de 110°'a göre anlamlı şekilde yüksek olduğu bulundu.*
Sonuç: *Bulgular, eklem açısının hem BB hem de TB kasları için MVIC sırasında EMG RMS genliği değerlerini önemli ölçüde etkilediğini göstermiştir. Bu bulgular, egzersiz reçetesi ve rehabilitasyonda eklem açısının seçiminin önemini vurgulamaktadır.*
Anahtar kelimeler: *Elektromiyografi, Dirsek eklemi, Biceps brachii, Triceps brachii, İzometrik kasılma.*

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INTRODUCTION

The force output of a muscle depends on both the recruitment patterns of motor units and the biomechanical characteristics of the muscle fibres and the muscle-tendon complex. Numerous studies have shown that changes in joint angle or muscle length significantly influence the maximal force a muscle can generate.[1] Muscle fibre length and the speed at which it changes directly influence the peak force a muscle can produce, as explained by the well-known force-length and force-velocity principles. When examining isometric contractions, it is essential to account for both muscle length and joint position as key factors affecting the estimation of maximal muscle force.[2] Despite existing research, how joint position influences motoneuron excitability patterns is not yet fully understood. Consequently, the extent to which joint angle alters the relationship between surface electromyography (EMG) signals and force production remains uncertain. These aspects are particularly important when estimating muscle force from surface EMG, as accurate neuromusculoskeletal (NMS) modelling depends on understanding the interdependent effects of joint angle, EMG amplitude, and force output.[3,4]

Many NMS models presented in the literature employ EMG data to predict muscle forces or activation levels.[5] It is essential to have a comprehensive understanding of the interrelationships between EMG, force, and joint angle to accurately model the dynamic NMS. It is conceivable that the joint angle exerts an influence on muscle recruitment or velocity coding strategies, or differential recruitment between muscles, which may in turn alter the force-EMG relationship.[6] In order for the muscles to be loaded correctly during exercises, reference values of maximum voluntary isometric contraction (MVIC) percentages at certain joint angles need to be determined. According to Boettcher et al. reference values obtained from MVIC data are essential for the normalisation of EMG signals.[7]

Several researchers have documented a systematic influence of muscle length or joint angle on EMG amplitude during MVIC regarding with the quadriceps femoris muscle,[2,3] the soleus and gastrocnemius muscles,[8] the knee extensors,[9] the biceps femoris muscle[10] and the tibialis anterior muscle.[11] In contrast, a reduction in EMG data has been observed with decreasing muscle length, as reported for the gastrocnemius[12] and quadriceps.[2] Recent evidence confirms that eccentric muscle force exceeds isometric force even in the early phase of elbow flexion. Linnamo et al.[13] demonstrated that maximal eccentric force produced by the biceps brachii (BB) and brachioradialis within the first 10° of elbow movement was significantly greater than the isometric pre-activation force measured at 80° and 110° joint angles. This early-phase enhancement was also accompanied by a steeper decline in EMG amplitude with increasing joint angle in eccentric actions. Supporting these findings, Yoshida et al.[14] reported that maximal eccentric elbow flexion strength was significantly greater than isometric strength by approximately 11.7% in healthy adults. Moreover, they demonstrated that eccentric force could be reliably estimated from isometric force and muscle thickness using regression models, providing a practical alternative to direct eccentric measurement in clinical and sports settings. However, studies on the elbow joint have indicated that alterations in joint angle do not significantly influence EMG levels during MVIC. Doheny et al.[15] showed that while MVIC torque varied across eight elbow angles, EMG amplitude during maximal voluntary contractions remained statistically unchanged in BB, brachioradialis, and triceps brachii (TB). Similarly, Akima et al.[1] found no significant effect of elbow angle (60°, 90°, 120°) on EMG root mean square (RMS) during isometric extension at submaximal to maximal levels, suggesting consistent neuromuscular activation despite changes in joint position. The variability in results suggests that the link between muscle length and peak EMG amplitude is likely influenced by the anatomical or functional characteristics of the particular muscle or joint involved.

We hypothesized that both BB and TB would exhibit the highest EMG RMS amplitudes at approximately 70° of elbow flexion, corresponding to the optimal muscle length for neuromuscular activation. This study did not measure actual force or torque output but focused solely on surface EMG amplitude. The aim of the study was to compare EMG RMS amplitudes recorded from the BB and TB muscles during MVIC at different elbow angles and to determine which angle provides optimum efficiency according to this comparison.

METHODS

Participants

This study employed a cross-sectional experimental design to compare the EMG activity of BB and TB during MVIC at different elbow joint angles. The study was approved by the Health Research Ethics Committee of Ordu University (Approval No: 2022/33) and conducted in accordance with the Declaration of Helsinki. Thirty participants (15 females and 15 males; age=20.56±1.07 years, BMI=22.16±2.27 kg/m^2) volunteered (Table 1). Inclusion criteria were being between 18 and 24 years of age, having no history of joint injuries in the past six months, no contraindications for engaging in upper extremity exercise, and willingness to voluntarily participate in the study. Participants with neuromuscular disorders, orthopaedic injuries, or active skin injuries/dermatological conditions were excluded. All participants completed a health screening questionnaire and provided written informed consent prior to participation. Data collection took place during a single session in the Performance Laboratory of the Faculty of Sport Sciences at Ordu University.

Data Collection

Data were collected from the elbow joint at various joint angles to provide input parameters for a physiologically based NMS model.[16] In alignment with this model, measurements were performed at three different elbow flexion angles (70°, 90°, and 110°) to record EMG amplitudes during MVIC of BB and TB muscles. EMG signals were recorded from the BB (during elbow flexion) and TB (during elbow extension) muscles, and MVIC testing was conducted to determine muscle activation levels. Participants were seated upright on a chair with the trunk and scapula stabilized against the chair back, and the shoulder maintained in a neutral position (0-10° abduction, neutral flexion/extension). The forearm was kept in a neutral position between pronation and supination to standardize activation, while the wrist was maintained in neutral alignment (0° flexion/extension, 0° radial/ulnar deviation). Elbow joint angles of 70°, 90°, and 110° were tested in a randomized order to avoid sequence and fatigue effects, and the order of BB and TB testing was counterbalanced across participants. For BB measurements, participants performed elbow flexion by exerting MVIC against resistance applied via a belt secured to the distal forearm just proximal to the wrist joint, with the upper arm fixed to the trunk to minimize compensatory movements (Figure 1). TB activity was assessed in an overhead elbow position, where participants generated maximum voluntary isometric contraction by extending the elbow against the resistance of the belt while maintaining the arm overhead. In both tasks, no visible joint movement occurred, ensuring that only isometric contractions were measured (Figure 2).

Figure 1. Experimental setup for BB MVIC. The arrow indicates the direction of applied resistance; no joint movement occurred during MVIC.

Figure 2. Experimental setup for TB MVIC. The arrow indicates the direction of applied resistance; no joint movement occurred during MVIC.

According to the protocol described by Konrad,[17] participants were instructed to gradually increase their force, reach their maximum effort within 3-5 seconds, and maintain that effort for an additional 3 seconds. Each condition was repeated three times with 30-60 s rest between trials. Order of conditions

was randomized to reduce fatigue and sequence bias. During all MVIC trials, contractions were strictly isometric with no visible joint movement. Resistance was applied only to maintain the predetermined joint angle, while the upper arm and trunk were stabilized against the chair back. This ensured that EMG signals represented isometric activation without confounding effects of dynamic movement. All measurements were obtained from the dominant upper limb of each participant to ensure consistency in neuromuscular activation and joint function. EMG data were sampled at 1000 Hz using wireless Ag/AgCl surface electrodes connected to a Noraxon myoMUSCLE system (Noraxon, Scottsdale, AZ, USA). Electrode placement was performed in accordance with the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines. To ensure standardization, all participants were instructed and monitored by the same investigator, and verbal encouragement was provided consistently. Joint angles were confirmed using an electrogoniometer (Noraxon, Scottsdale, AZ, USA).

Signal process

Raw EMG signals obtained during MVIC were processed offline to improve signal fidelity and reduce noise. Initially, a high-pass filter with a cutoff frequency of 10 Hz was applied to eliminate low-frequency movement artefacts and baseline drift, consistent with established recommendations.[17,18] A Butterworth approximation was employed to achieve a stable and phase-preserving frequency response. Subsequently, the signals were fully wave-rectified and smoothed using a moving RMS filter with a 200 ms time window, which is widely used for estimating the amplitude envelope of EMG signals in both static and dynamic tasks.[19,20] This RMS smoothing process enabled the quantification of muscle activation levels by providing reliable estimates of average and peak EMG amplitudes. The final MVIC data presented in this study (mean, peak, and minimum values) were extracted from the RMS-processed EMG signal for each muscle, ensuring that comparisons across subjects and muscles were based on standardized and physiologically meaningful metrics.

Statistical analysis

All statistical analyses were performed using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics, including mean and standard deviation (SD), were used to summarize the data. The normality of the EMG values obtained from BB and TB muscles at 70°, 90°, and 110° during MVIC was assessed using the Shapiro-Wilk test, which indicated that the data were not normally distributed. Consequently, the non-parametric Friedman test was employed to assess whether significant differences existed among the EMG values across joint angles. Post hoc pairwise comparisons were conducted using the Wilcoxon signed-rank test. To control for the Type I error associated with multiple comparisons, Bonferroni correction was applied by dividing the standard significance level ($\alpha=0.05$) by the number of comparisons ($k=3$), resulting in an adjusted threshold of $p < 0.017$ (i.e., $\alpha'=0.05/3$). Accordingly, p-values less than 0.017 were considered statistically significant in the pairwise Wilcoxon tests.

RESULTS

For BB, EMG RMS amplitude during MVIC was significantly affected by elbow joint angle ($\chi^2(2)=12.867$, $p=0.002$, $W=0.214$). Median EMG amplitude was highest at 70° (1260.5 µV [874.3-1543.5]) compared to 90° and 110°. Similarly, TB activation differed significantly across joint angles ($\chi^2(2)=15.748$, $p <0.001$, $W=0.262$), with the highest values observed at 70° (521.5 µV [338.5-646.5]) (Table 2).

In addition, the BB/TB EMG RMS ratio was approximately 2.42 at 70°, 1.62 at 90°, and 2.05 at 110°, indicating consistently greater activation of BB compared with TB across all tested joint angles.

Post-hoc pairwise comparisons indicated that BB activation was significantly greater at 70° compared to both 90° ($Z=-3.610$, $p < 0.001$, $r=0.66$) and 110° ($Z=-2.880$, $p=0.004$, $r=0.53$). No significant difference was found between 90° and 110° ($Z=-0.524$, $p=0.600$, $r=0.10$). (Table 3).

Post-hoc analyses revealed that TB activation was significantly greater at 70° compared to both 90° ($Z=-2.443$, $p=0.015$, $r=0.45$) and 110° ($Z=-3.682$, $p < 0.001$, $r=0.67$). In addition, 90° produced significantly greater activation than 110° ($Z=-3.435$, $p=0.001$, $r=0.63$). (Table 3).

DISCUSSION

The purpose of this study was to compare BB and TB EMG RMS amplitudes across different elbow joint angles. The main finding was that both muscles showed the highest activation at 70°. The findings demonstrated that joint angle significantly influences the EMG activity of both BB and TB muscles during MVIC. The results indicated that both muscles exhibited significantly higher EMG amplitudes at 70°, suggesting that this joint position elicits the greatest neuromuscular activation.

These results align with Akima et al.[1] who reported that TB activation decreases at more extended angles (120° vs. 60°/90°). Conversely, Leedham and Dowling[21] found relatively stable BB EMG amplitudes across varying angles, suggesting muscle-specific recruitment regulation. Together, this evidence underlines the significance of joint angle in modulating motor unit recruitment and neuromuscular output.

The significantly greater BB activation at 70° than at 90° or 110° clearly supports the well-established length-tension relationship. This suggests that muscle force is maximised when the muscle is at its optimal length, i.e. not overly stretched or shortened.[22] Although actual torque/force was not measured in our study, the greater EMG RMS amplitudes observed at 70° suggest enhanced neuromuscular activation at this joint position. This finding is consistent with that of Liu et al.[23] who observed stable EMG signal quality at 90°, although maximal force production was not necessarily achieved at this angle. Onishi et al.[24] stated in a study on hamstring muscles that joint angle significantly affects both EMG activity and force output. This can be extrapolated to BB function. Our findings confirm that 70° offers clear biomechanical and neuromuscular advantages for BB isometric contraction. When more recent studies are examined, the significantly greater BB activation at 70° compared to 90° or 110° aligns with contemporary findings emphasizing the importance of optimal muscle length for neuromuscular excitation. Uwamahoro et al.[25] observed peak mechanomyographic (MMG) and torque responses of BB at mid-range angles, further supporting joint positioning as a key modulator of neuromuscular output. These findings reinforce our conclusion that the 70° elbow position elicits superior neuromuscular activation for BB MVIC and should be considered in both biomechanical modeling and functional assessment. Doheny et al.[15] conducted a study involving twelve volunteers (seven female and five male) and found similar results: the highest MVIC value was achieved at 70° for both extension and flexion. This result is consistent with the MVIC RMS results obtained at 70° in our study. Maximal force output diminishes at joint angles approaching biomechanical extremes, primarily due to alterations in anatomical parameters (e.g., reduced effectiveness of muscle moment arms), intrinsic muscular properties (e.g., suboptimal overlap of actin and myosin filaments as described by the force-length relationship), and potential neural modulation (e.g., afferent feedback from joint mechanoreceptors or the musculotendinous unit).

The TB muscle demonstrated the highest EMG RMS amplitudes obtained during MVIC at 70°, with significant reductions observed at 90° and 110°. The mean differences in EMG values obtained from the TB muscle at angles of 90° and 110° were compared. The results of this comparison indicate that the mean EMG RMS amplitudes obtained during MVIC obtained at 90° were higher than the mean EMG RMS amplitudes obtained during MVIC obtained at 110°. This pattern is consistent with the findings of Akima et al.[1] who examined the three heads of the TB (medial, lateral, and long) and reported higher RMS values at 60° and 90°, with a marked decline at 120°. The results of this study highlight the mechanical disadvantage and reduced neural recruitment that occur as the elbow approaches full extension.

In the literature, there are studies in which not only MVIC RMS values but also MVIC force were assessed across joint angles. For the elbow, Miller et al.[26] reported that performance-related feedback, particularly the combination of visual and verbal cues, significantly enhanced MVIC force in the elbow flexors. This highlights the role of sensory feedback in modulating maximal neuromuscular output. At the ankle, a study

Table 1. Participant characteristics.

	Females (n=15) Mean±SD	Males (n=15) Mean±SD	Total (N=30) Mean±SD
Age (years)	20.46±1.35	20.66±0.72	20.56±1.07
Height (cm)	168.86±6.35	178.93±6.72	173.90±8.21
Weight (kg)	61.13±8.70	73.66±9.33	67.40±10.92
Body mass index (kg/m^2)	21.40±2.59	22.92±1.64	22.16±2.27

Table 2. Median [IQR] of EMG Root Mean Square (RMS) amplitudes (μV) at different angles (N=30).

		Median [IQR] (μV)	X^2	df	p/Kendall's W
Biceps brachii	70°	1260.5 [874.3 - 1543.5]			
	90°	744.0 [574.8 - 1199.3]	12.867	2	0.002/0.214
	110°	752.0 [505.3 - 1151.5]			
Triceps brachii	70°	521.5 [338.5 - 646.5]			
	90°	460.0 [274.5 - 540.8]	15.748	2	<0.001/0.262
	110°	367.5 [227.0 - 519.3]			

IQR: Interquartile Range. Kendall's W was reported as the effect size for Friedman tests.

Table 3. Pairwise Wilcoxon Signed-Rank Test results for biceps brachii and triceps brachii (Median [IQR], z, p,r) (N=30).

		Median [IQR] (μV)	z	r	p
Biceps brachii					
70° vs 90°	70°	1260.5 [874.3 - 1543.5]	-3.61	0.66	<0.001
	90°	744.0 [574.8 - 1199.3]			
70° vs 110°	70°	1260.5 [874.3 - 1543.5]	-2.88	0.53	0.004
	110°	752.0 [505.3 - 1151.5]			
90° vs 110°	90°	744.0 [574.8 - 1199.3]	-0.52	0.10	0.600
	110°	752.0 [505.3 - 1151.5]			
Triceps brachii					
70° vs 90°	70°	521.5 [338.5 - 646.5]	-2.44	0.45	0.015
	90°	460.0 [274.5 - 540.8]			
70° vs 110°	70°	521.5 [338.5 - 646.5]	-3.68	0.67	<0.001
	110°	367.5 [227.0 - 519.3]			
90° vs 110°	90°	460.0 [274.5 - 540.8]	-3.44	0.63	0.001
	110°	367.5 [227.0 - 519.3]			

Values are presented as Median [IQR]. Effect sizes for Wilcoxon signed-rank tests were reported as $r = Z/\sqrt{N}$.

found that plantarflexion MVIC torque and medial gastrocnemius EMG amplitude were highest near neutral ankle position, and decreased as the joint moved into dorsiflexion or plantarflexion extremes.[27] These findings consistently show that EMG RMS amplitudes obtained during MVIC, in terms of both electrical activation and force, tend to decrease as the muscle moves away from its optimal length, confirming the length-dependent behaviour across multiple joints. In the literature, there are studies in which not only the MVIC RMS values of the joint angle but also the MVIC force were investigated. In these studies, joint angle was found to have a significant effect on the resulting MVIC force for both flexion and extension of the elbow joint,[28,29] knee joint[30] and ankle joint.[8] EMG RMS amplitudes obtained during MVIC decreased with increasing muscle length. Linnamo et al.[13] measured maximal voluntary MVIC RMS of elbow flexion in ten healthy male volunteers during isometric and isokinetic eccentric motion at 80° and 110° and 140° elbow angle. The study reported a significant effect of joint angle on EMG RMS during maximal voluntary contractions. The results of this study are similar to our study.

Uwamahoro et al.[25] analysed the effects of elbow joint angles on the elbow flexion torque and MMG. Their results demonstrated that both MMG RMS and torque RMS values progressively increased as the joint angle shifted from 10° to 60°, followed by a decline at more extended joint positions beyond this range. It was demonstrated that increases in the elbow flexion angle in excess of 60° resulted in a downward shift in the torque RMS. The findings indicate that near the resting muscle length approximately at 60° crossbridge formation between actin and myosin filaments is optimized. The observed reductions in force at shorter muscle lengths are likely due to filament overlap interference among adjacent actin strands, whereas at longer lengths, diminished force output is attributed to excessive separation and reduced overlap between actin and myosin filaments.[31] Furthermore, given that BB inserts at the radial tuberosity, elbow flexion causes a shortening of the muscle due to changes in the muscle's moment arm geometry. These biomechanical alterations not only influence the muscle's mechanical advantage but are also associated with neural adaptations. Specifically, variations in BB length during elbow flexion have been shown to affect surface EMG amplitude, likely due to changes in motor unit recruitment thresholds, firing rates, and the synchronization of active motor units. Moreover, the modified muscle tendon dynamics at different joint angles may influence afferent feedback from muscle spindles and golgi tendon organs, further modulating the level of neural drive delivered to the muscle. These findings also support the results of our study.

The present findings provide additional evidence regarding angle-dependent neuromuscular activation of the elbow flexors and extensors. While it is physiologically established that muscles generate maximal force near their optimal length, our study contributes by characterizing EMG RMS amplitude profiles of both BB and TB across multiple joint angles within the same cohort. This dual-muscle perspective adds novel comparative information to the literature. These results also have implications for neuromuscular efficiency, a concept describing the ratio between neural activation and muscular output.[22,1] The observed angle-dependent variations in EMG activity may reflect changes in neural drive required to maintain isometric contractions at different muscle lengths. Moreover, the BB/TB EMG RMS ratio exceeded 1.0 at all joint angles, with the highest value at 70°.[2] This finding highlights the dominance of BB activation relative to TB in isometric elbow flexion, which may provide further context for understanding co-activation patterns and joint stabilization strategies. Although our data are limited to isometric conditions, the identification of joint angles eliciting greater neuromuscular activation may inform exercise prescription and rehabilitation design. However, direct extrapolation to injury prevention protocols should be made with caution, as such applications require longitudinal and dynamic assessments.

Limitations

The primary limitation of this study is the potential for electrode displacement relative to the underlying muscle due to changes in elbow positioning, which may alter the spatial relationship between the electrode and the muscle fibres, thereby affecting the fidelity of the EMG signal and the accuracy of subsequent

measurements.[32] Given the inherent limitations of surface EMG, it is not feasible to entirely control for electrode shift, making it difficult to definitively attribute observed changes in EMG amplitude to either alterations in muscle length or electrode displacement. The second limitation is that this study assessed only isometric muscle contractions; thus, the results may not generalize to dynamic movement patterns (e.g., concentric or eccentric actions). The third limitation is that the TB muscle's three heads were not evaluated individually. The fourth limitation of this study is that actual torque or force production was not directly measured; only surface EMG RMS amplitudes were analysed. Therefore, interpretations are limited to neuromuscular activation and cannot be generalized to mechanical force output. Future research should consider differential activation across the medial, lateral, and long heads.

Conclusion

In conclusion, the present study reinforces the critical influence of elbow joint angle on both muscle activation and force production during isometric contractions of the upper arm. The findings demonstrate that a joint angle of 70° optimizes EMG RMS activity recorded during MVIC for the BB and TB muscles, aligning with the established length-tension relationship and previous literature. These results underscore neuromuscular activation, as reflected by EMG RMS amplitude, is greatest when the muscle operates at an optimal length, rather than at more extended or flexed positions. Moreover, the observed stability of EMG signals around 90°, despite not coinciding with peak force output, highlights the complex interplay between neuromuscular activation and biomechanical advantage. Collectively, these insights provide valuable implications for both clinical assessment and the design of training or rehabilitation protocols, emphasizing the importance of joint angle selection to optimize neuromuscular activation and potentially enhance functional outcomes.

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