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ANTAGONIST MUSCLE ACTIVATION DURING ISOMETRIC ELBOW FLEXION AT VARIED JOINT ANGLES: A COMPARATIVE NEUROMUSCULAR ANALYSIS BETWEEN VOLLEYBALL PLAYERS AND SEDENTARY ADULTS

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Abstract

Neuromuscular coordination enhances athletic performance and prevents injuries. Antagonist muscle activation during isometric movements, such as elbow flexion, is crucial for joint stability and efficiency. Volleyball-specific training may lead to distinct neuromuscular adaptations, which differ from those of sedentary individuals. This study aims to explore the differences in antagonist muscle activation during isometric elbow flexion, comparing volleyball players with sedentary adults, with a focus on neuromuscular control and the effects of co-contraction. Twenty-eight males (14 volleyball players and 14 sedentary individuals; ages 18–25) participated in the study. Surface electromyography (EMG) recorded biceps and triceps activity at 45°, 90°, and 120° elbow angles. EMG activity, co-contraction indices (CCIs), and perceived exertion (RPE) were statistically analysed using descriptive statistics and two-way repeated measures Analysis of Variance. Bonferroni corrections assessed angle-specific effects. Significance levels (α) were set to 0.05 for all analyses. Athletes exhibited significantly higher biceps activation (mean EMG_{max} = 0.63 vs. 0.48) and lower triceps activation (mean EMG_{max} = 0.25 vs. 0.35, $p <$ 0.001). Co-contraction (CCI) was lower among athletes (mean = 0.55 vs. 0.89). RPE scores were consistently lower in athletes (mean = 12.8 ± 1.6) compared to non-athletes (15.7 ± 1.5), indicating superior neuromuscular efficiency. Volleyball players demonstrated enhanced neuromuscular control, as evidenced by higher agonist activation, reduced antagonist activation, and lower co-contraction. The enhanced neuromuscular adaptations of volleyball players, likely resulting from consistent training, suggest improved movement mechanics and a reduced risk of injury. Future longitudinal studies are advised to explore causality and sport-specific neuromuscular changes.

Keywords*: electromyography, exercise, isometric contraction, muscle strength, upper arm, volleyball*

THEORETICAL BACKGROUND

The optimization of human motion is fundamentally rooted in the principle of neuromuscular efficiency, wherein the central nervous system (CNS) coordinates muscular contractions to generate the desired force with minimal metabolic and neural expenditures (ENOKA, 1996). The study of muscle coordination during human movement remains an interesting area of research within exercise science and sports medicine. During both static and dynamic movements, muscles do not function in isolation; instead, they work in conjunction with one another. Antagonist muscles, which oppose the movement of primary or agonist muscles, play a crucial role in stabilizing joints to ensure smooth and controlled movement (HUNTER et al., 2002). The activation of antagonist muscles during movement tasks is crucial for optimizing

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force production, preventing injuries, and ensuring effective movement coordination (GRUBER - GOLLHOFER, 2004). While co-activation plays a significant role in enhancing joint stability, especially during complex tasks, excessive co-contraction may lead to inefficient movement patterns, increased energy expenditure, and premature fatigue, ultimately resulting in injury (LATASH, 2008). The CNS's ability to modulate this balance is a key aspect of motor skill acquisition and is significantly influenced by long-term physical training (AAGAARD et al., 2002). The muscle co-activation becomes particularly noteworthy when comparing trained athletes to sedentary individuals, as their neuromuscular systems have undergone significantly different adaptations due to their respective training regimens or lifestyle choices. The nature of volleyball involves significant amounts of explosive upper limb movements, which require both agonist muscle strength and control of the antagonist in the execution of tasks such as ball control, spiking, blocking, and serving (HEWIT et al., 2011). Most studies have focused on sport-specific dynamic movements, yet these actions are fundamentally built upon the ability to precisely regulate isometric force at varying joint positions (FOLLAND - WILLIAMS, 2007). Furthermore, while it is established that antagonist co-activation varies as a function of joint angle to maintain joint integrity, it remains unclear how these angle-dependent strategies are modified by long-term athletic training (KUBO et al., 2004). Moreover, the relationship between objective measures of neuromuscular efficiency and the subjective perception of effort remains poorly characterized in this context. The Rate of Perceived Exertion (RPE) is a broadly used psychophysiological tool that reflects a complex integration of afferent feedback from central and peripheral sources (BORG, 1982; HUTCHINSON et al., 2021; MARCORA, 2009). Investigating whether the presumed neuromuscular efficiency of athletes corresponds to a lower RPE during a standardized isometric task could provide valuable insights into the interplay between neural adaptation and effort perception, with direct implications for training monitoring and fatigue management. Co-contraction refers to the simultaneous activation of both agonist and antagonist muscles surrounding a joint, which plays a crucial role in maintaining joint stability, enhancing motor control, and improving movement precision. Despite the recognized importance of antagonist muscle activation in joint stability and performance, most research has focused on agonist function or dynamic movement patterns, with relatively few studies examining antagonist behaviour during isometric contractions, particularly in the context of sport-specific adaptations (CAROLAN - CAFARELLI, 1992; KUBO et al., 2004). Isometric tasks, such as static elbow flexion, provide a controlled setting to investigate neuromuscular coordination and the efficiency of co-contraction strategies (CHOWDHURY et al., 2013; Mc DONAGH et al., 1983). The degree of antagonist activation during isometric efforts is influenced by joint angle, with increased co-contraction observed at extreme positions to enhance joint stability (HUNTER et al., 2002; KUBO et al., 2004). Assessing and interpreting antagonist contraction during muscle contractions is crucial for understanding the dynamics of movement, particularly in the field of sports science. Quantifying joint stiffness presents challenges when employing either experimental or computational methods; therefore, electromyographic quantification is preferred due to its relative ease and effectiveness (LI et al., 2021). Electromyography (EMG) is the most widely used method for recording the electrical activity of muscles during dynamic and static tasks, revealing the timing and magnitude of muscle activation (ROBERTS - GABALDON, 2008). The co-contraction index (CCI) is used to quantify the simultaneous activation of agonist and antagonist muscles during movement (FALCONER - WINTER. It is calculated as a sum of both agonist and antagonist EMG activity (Equation 1). The CCI increases with greater co-contraction, suggesting that the antagonist is taking a more significant role in stabilizing the joint or resisting movement.

Equation 1: Calculation of Co-contraction Index (FALCONER-WINTER, 1985)

$$CCI \frac{2 \times EMG\ of\ antagonist\ muscle}{EMG\ of\ agonist\ Muscle}$$

In theory, athletes must have less muscle co-activation and better muscle efficiency during static exercises than people who lead a sedentary lifestyle. This is because athletes' bodies adapt to reduce unnecessary muscle work and energy use. (CAROLAN - CAFARELLI, 1992; TILLIN et al., 2010). However, it is unclear how these changes occur at different joint angles or how they relate to the perceived difficulty of the exercise. For volleyball players, repeated task-specific exposure to repeated explosive actions may "condition" the CNS to recruit muscles more efficiently with enhanced force production and reduced unwanted antagonist activity. (GABRIEL et al., 2006). On the contrary, non-athletes are exposed to a lower demand for movement-specific variability, leading to a greater activation of the antagonists during isometric contractions, as a compensation strategy. (HORTOBÁGYI - DEVITA, 2000). Given these gaps, the present study aims to objectively compare antagonist muscle activation patterns during isometric elbow flexion at varied joint angles between trained volleyball players and sedentary adults. By quantifying muscle activity, co-contraction indices, and perceived exertion, this research seeks to (i) compare agonist and antagonist muscle activity between volleyball players and sedentary adults; (ii) determine how these neuromuscular variables are modulated by elbow joint angle (45°, 90°, and 120° of elbow flexion); and (iii) assess the relationship between objective neuromuscular activity and the subjective RPE.

METHODS

SELECTION OF THE PARTICIPANTS

The research was conducted at the Sports and Exercise Physiology Laboratory, with approval from the institution's Human Ethics Committee (Reference No. SC/HEC/2025/P1B, Date: 10 February 2025), in accordance with the Declaration of Helsinki of 1975. The study involved 14 young male college students and 14 trained volleyball players, all of whom were between 18 and 25 years old. Participants were selected through a random sampling method, adhering to specific inclusion and exclusion criteria, to ensure each individual had an equal opportunity to be selected. Prior to the experiment, the study's purpose was clearly explained to the participants, and only those who consented were included. Written consent was obtained from all participants, who voluntarily agreed to join the study. They were allowed to rest for

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10 minutes in a seated position in the laboratory, maintained at a temperature of 25°C, while a digital hygrometer recorded the average relative humidity over the 10-day experimental period.

Inclusion criteria [N = 28; Sedentary adults (n=14), Volleyball players (n=14)**]**

- Age range 18–25 years
- Having no prior complaints regarding any diseases (neuromuscular, pulmonary, etc.)
- Willing to participate voluntarily

Exclusion criteria:

- Age ranges <18 years or >25 years
- Having any complaints regarding any prior diseases (neuromuscular, pulmonary, etc.)
- Not willing to participate in the study voluntarily

ANTHROPOMETRIC MEASUREMENTS

STATURE

Stature was measured by 'Seca 213 Portable Stadiometer' (*Seca Deutschland, Hamburg, Germany*, range of measurement 60–220 cm) by the 'Stretch Stature Method. (CHATTERJEE - BANDYOPADHYAY, 2022; SABA et al., 2023; STEWART et al., 2011).

BODY COMPOSITION

Bioimpedance analysis (BIA) method was used to measure the body compositions, e.g., weight, lean body mass, fat percentage, and body mass index (BMI) using 'Tanita BC601 Inner scan Segmental Body Composition Monitor' (*Tanita Corporation, Japan*) with scientifically validated accuracy. (DELISLE NYSTRÖM et al., 2016; SABA et al., 2023). After manually entering the subject's height, weight, gender, and age, the measurements were obtained using the standard configuration.

PHYSIOLOGICAL MEASUREMENTS

ELECTROMYOGRAPHIC (EMG) RECORDING

The iWork 214 (*Dover, United States*) EMG recording kit was set up and prepared for recording. The electrical activity was recorded from two different muscles, the biceps brachii and the Triceps brachii, using surface EMG. The muscles were isolated by manual muscle testing, and the leads were placed according to the SENIAM guidelines. The skin preparation has been done correctly to record a clear signal using a surface electrode (CHATTERJEE et al.,2021). The amplifier was set up, and an EMG recording was performed using the software '*Labscribe'* in the computer (CHATTERJEE - BANDYOPADHYAY, 2022). The muscle's electrical activity was assessed at three distinct elbow angles, 45°, 90°, and 120°, from both muscles. Participants used a 4 kg dumbbell for the experiment, holding it for a minimum of 30 seconds or until they reached fatigue and could no longer maintain the hold. This procedure was repeated for each of the three elbow angles, with their RPE recorded after each trial. The

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participants at these three angles followed the same protocol, but this time the electrodes were positioned on the triceps brachii.

BORG'S SCALE OF PERCEIVED EXERTION (RPE)

The rating of perceived exertion (RPE) is used to gauge exercise intensity without relying on physiological indicators such as peak oxygen uptake, heart rate, and lactate concentrations. (HUTCHINSON et al., 2021). The Borg RPE scale, created by Gunnar Borg, measures the strenuousness of an activity by considering factors such as heart rate, respiratory rate, heavy sweating, and muscle effort.

STATISTICAL ANALYSIS

A comprehensive statistical plan was implemented to identify group-specific neuromuscular adaptations. The Shapiro-Wilk test for normality showed that the data did not maintain a normal distribution. Statistical analyses were performed using IBM's Statistical Package for Social Sciences (SPSS) version 29.

1. **Descriptive Analysis:**
    - Mean and standard deviation were calculated for all general and other experimental variables (e.g., EMG activity, CCI, and RPE) across groups and elbow angles.
2. **Mixed 2×3 ANOVA:**
    - Two-way analysis of variance (ANOVA) with repeated measures was applied for comparing two independent groups across multiple repeated conditions:
        - **Between-Subjects Factor:** Group (volleyball players vs. sedentary adults).
        - **Within-Subjects Factor:** Elbow angle (45°, 90°, 120°).
    - Separate ANOVAs were run for each dependent variable, i.e., Biceps EMG_{max}, Biceps muscle activity (RMS), Triceps EMG_{max}, Triceps muscle activity (RMS), Co-contraction index (CCI), and Borg's RPE.
3. **Mauchly's Test of Sphericity** was applied to verify sphericity assumptions for each within-subject variable. For variables where sphericity was not met, Greenhouse-Geisser corrections were applied to adjust the degrees of freedom. However, none of the variables violate the sphericity assumption; therefore, the correction method was skipped.
4. **Post-Hoc Comparisons:**
    - Bonferroni corrections were applied to pairwise comparisons to explore significant main effects or interactions further. This method controls Type I errors while accounting for multiple comparisons.

RESULTS

SAMPLE CHARACTERISTICS

Both groups comprised 14 young adults (N = 28; age: athletes = 19.50 ± 1.23 years, non-athletes = 19.86 ± 1.17 years). Athletes were markedly taller (176.5 ± 10.1 cm vs 158.5 ± 41.2 cm) yet weighed only slightly more (67.9 ± 10.9 kg vs 65.9 ± 11.6 kg), yielding a lower body-mass index (21.7 ± 2.6 vs 23.1 ± 3.7 kg m^{-2}). Resting physiological measures reflected better cardiovascular fitness in the athletic group: the pre-exercise heart rate averaged 75 ± 14 bpm, compared with 86.7 ± 14.0 bpm in the controls, and the post-exercise heart rate remained lower as well (75.4 ± 9.4 vs 86.8 ± 12.6 bpm). Athletes also showed a slightly higher resting systolic blood pressure within the normal range before exercise (121.6 ± 9.5 vs 111.9 ± 27.5 mmHg), but smaller post-exercise rises in both systolic and diastolic pressures. Body-composition indices favoured the athletes, who had greater absolute muscle mass (51.2 ± 7.6 kg vs. 47.5 ± 5.7 kg) and bone mass (3.16 ± 0.56 kg vs. 2.84 ± 0.38 kg), along with a lower body-fat percentage (20.7 ± 5.9% vs. 22.4 ± 7.2%) and a lower visceral fat rating. Despite similar daily caloric intakes (~2,500 kcal/day), athletes displayed a lower metabolic age (19.8 ± 5.3 years vs. 24.7 ± 10.0 years), underscoring their superior metabolic profile. Overall, the two cohorts were closely matched for chronological age and body mass but differed in stature, cardiovascular markers, and body composition, with athletes exhibiting characteristic adaptations associated with regular training.

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Table 1: Mean and standard deviation of general physical and physiological variables of athletes (n=14) and non-athletes (n=14).

Variables	**Non-athletes (Sedentary Adults)**			**Athletes (Volleyball players)**		
	N	**Mean**	**SD**	**N**	**Mean**	**SD**
Age (yrs)	14	19.86	1.17	14	19.50	1.23
Height (cm)	14	158.53	41.17	14	176.51	10.06
Weight (Kg)	14	65.86	11.61	14	67.87	10.93
BMI (kg/m²)	14	23.06	3.67	14	21.69	2.59
Pre-Exercise Heart Rate (BPM)	14	86.71	13.99	14	75.00	13.95
Post-Exercise Heart Rate (BPM)	14	86.79	12.57	14	75.36	9.37
Pre-Exercise Systolic Blood Pressure (mm Hg)	14	111.86	27.48	14	121.57	9.45
Pre-Exercise Diastolic Blood Pressure (mm Hg)	14	77.00	7.02	14	75.86	7.94
Post-Exercise Systolic Blood Pressure (mm Hg)	14	128.36	9.30	14	121.93	11.07
Post-Exercise Diastolic Blood Pressure (mm Hg)	14	81.64	14.98	14	76.07	7.88
Body Fat (%)	14	22.38	7.23	14	20.69	5.87
Muscle Mass (Kg)	14	47.53	5.67	14	51.16	7.63
Bone Mass (Kg)	14	2.84	0.38	14	3.16	0.56
Daily Calorie Intake (Kcal)	14	2554.00	403.75	14	2472.00	387.97
Metabolic age (yrs)	14	24.71	10.02	14	19.79	5.32
Body Water (%)	14	5.07	3.29	14	3.93	2.40
Visceral Fat (Kg)	14	89.48	24.64	14	95.80	0.93
Body Temp (°F)	14	50.36	4.23	14	53.51	3.24

FORCE AND EMG ANALYSIS

This study aimed to investigate the differences in antagonist activation and co-contraction index (CCI) between athletes and non-athletes during isometric elbow flexion at various joint angles (45°, 90°, and 120°). The results are organized into several subsections covering between-group comparisons, within-subject effects, and specifics on muscle activation and perceived exertion.

BETWEEN-GROUP EFFECT ANALYSIS

Biceps EMG Activity

A significant main effect was found for group differences in Biceps EMG activity. The athletes showcased significantly higher Biceps EMG_{max} values compared to non-athletes across all angles: Athletes (Mean = 0.63, SD = 0.08); Non-athletes (Mean = 0.48, SD = 0.07). The analysis revealed a statistically significant difference: $F(1, 26) = 100.44$, $p < .001$, with a partial eta squared (η^2) of 0.79, indicating a large effect size (Figure 1a, 1b).

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Triceps EMG Activity

Conversely, non-athletes exhibited higher Triceps EMG activity: Athletes (Mean = 0.25, SD = 0.05); Non-athletes (Mean = 0.35, SD = 0.06). Statistical analysis confirmed a significant effect for the Triceps EMG_{max}: $F(1, 26) = 111.79$, $p < .001$, $\eta^2 = 0.81$, also indicating a large effect size. This suggests that non-athletes may rely more on antagonist muscle activation during isometric contractions (Figures 1c and 1d).

Table 2: Tests of Between-Subjects Effects for Group Differences in EMG Amplitudes, Co-contraction Index, and Perceived Exertion

Tests of Between-Subjects Effects					
Measure	**Df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Biceps EMG_{max}	1, 26	0.431	100.440	***0.000***	0.794
Biceps muscle activity (RMS)	1, 26	0.299	138.375	***0.000***	0.842
Triceps EMG_{max}	1, 26	0.337	111.786	***0.000***	0.811
Triceps muscle activity (RMS)	1, 26	0.149	95.370	***0.000***	0.786
CCI	1, 26	3.075	269.901	***0.000***	0.912
RPE	1, 26	192.012	106.489	***0.000***	0.804
***p<0.05, Statistically significant**					

Co-contraction Index (CCI)

The CCI analysis indicated a significantly lower antagonist-to-agonist ratio in athletes across all angles: Athletes (Mean = 0.55, SD = 0.07); Non-athletes (Mean = 0.89, SD = 0.09). The analysis revealed a significant group effect: $F(1, 26) = 269.90$, $p < .001$, $\eta^2 = 0.91$, indicating a huge effect size (Figure 1e). The CCI increased progressively with elbow angle, particularly at 120° (Table 4).

Angle-Dependent Effects

Within-subject analyses revealed significant effects of elbow angle on muscle activation patterns.

- For Triceps EMG_{max}: $F(2, 52) = 4.57$, $p = .015$, $\eta^2 = 0.15$, indicating the activation patterns varied with elbow flexion angles.
- For Triceps RMS: $F(2, 52) = 5.97$, $p = .005$, $\eta^2 = 0.19$, suggesting enhanced triceps activation at increased angles.

Post-hoc pairwise comparisons using Bonferroni adjustments revealed significant differences in Triceps RMS between 45° vs 120° (p = .015), 90° vs 120° (p = .020).

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Rating of Perceived Exertion (RPE)

The RPE findings indicated that athletes reported lower exertion levels at all angles, with athletes (Mean = 12.8, SD = 1.6) and Non-Athletes (Mean = 15.7, SD = 1.5) showing significant differences. The statistical analysis yielded a significant group effect, $F(1, 26) = 106.49$, $p < .001$, $\eta^2 = 0.80$, indicating that athletes experienced less perceived exertion during the tasks across all angles (Figure 1f).

Assumptions Check

Mauchly's test of sphericity was non-significant for all within-subject factors ($W = .88–1.00$, $p > .21$; Table 3); therefore, uncorrected F-values are reported.

Table 3: Mauchly's Test of Sphericity for the Within-Subject Factor (Elbow Angle) Across All Outcome Measures

Mauchly's Test of Sphericity				
Within-Subjects Effect	**Measure**	**Mauchly's W**	**df**	**p value**
Elbow Angle	Biceps EMG_{max}	0.980	2	0.781
	Biceps muscle activity (RMS)	0.997	2	0.968
	Triceps EMG_{max}	0.882	2	0.209
	Triceps muscle activity (RMS)	0.967	2	0.659
	CCI	0.882	2	0.209
	RPE	0.943	2	0.478

Interaction Effects

No significant Group × Angle interactions were observed for any measure:

- Biceps EMG_{max}: $F(2,52) = 0.046$, $p = 0.955$
- Triceps EMG_{max}: $F(2,52) = 1.909$, $p = 0.158$
- CCI: $F(2,52) = 2.196$, $p = 0.121$
- RPE: $F(2,52) = 1.558$, $p = 0.220$

These results demonstrate consistent differences between athletes and non-athletes in muscle activation patterns, with athletes showing more efficient neuromuscular control characterized by:

- Higher agonist activation
- Lower antagonist activation
- Reduced co-contraction
- Lower perceived exertion.

The differences were maintained across all joint angles, suggesting a generalized adaptation in motor control strategies.

Table 4: Repeated-Measures ANOVA: Within-Subject (Elbow Angle) and group × Angle Interaction Effects on Neuromuscular Variables

Repeated Measure ANOVA: Within-subject and Between-subject effects						
Source	**Measure**	**df1, df2**	**Mean Square**	**F**	**p value**	**Partial Eta Squared**
Group	Biceps EMG_{max}	1, 26	0.431	100.440	***0.000****	0.794
	Biceps muscle activity (RMS)	1, 26	0.299	138.375	***0.000****	0.842
	Triceps EMG_{max}	1, 26	0.337	111.786	***0.000****	0.811
	Triceps muscle activity (RMS)	1, 26	0.149	95.370	***0.000****	0.786
	CCI	1, 26	3.075	269.901	***0.000****	0.912
	RPE	1, 26	192.012	106.489	***0.000****	0.804
Elbow Angle	Biceps EMG_{max}	2, 52	0.000	0.039	0.962	0.001
	Biceps muscle activity (RMS)	2, 52	0.000	0.204	0.816	0.008
	Triceps EMG_{max}	2, 52	0.021	4.573	***0.015****	0.150
	Triceps muscle activity (RMS)	2, 52	0.011	5.974	***0.005****	0.187
	CCI	2, 52	0.048	3.465	***0.039****	0.118
	RPE	2, 52	96.583	99.499	***0.000****	0.793
Elbow Angle×Group	Biceps EMG_{max}	2, 52	0.000	0.046	0.955	0.002
	Biceps muscle activity (RMS)	2, 52	0.001	0.466	0.630	0.018
	Triceps EMG_{max}	2, 52	0.009	1.909	0.158	0.068
	Triceps muscle activity (RMS)	2, 52	0.005	2.620	0.082	0.092
	CCI	2, 52	0.030	2.196	0.121	0.078
	RPE	2, 52	1.512	1.558	0.220	0.057
***p<0.05, Statistically significant**						

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Table 5: Bonferroni-Adjusted Pairwise Comparisons Between Elbow Angles for Variables Showing Significant Angle Effects

Pairwise Comparisons Bonferroni					
Measure	**(I) Elbow Angle**	**(J) Elbow Angle**	**Mean Difference (I-J)**	**Std. Error**	**p-value**
Triceps EMG_{max}	**45°**	**90°**	-0.026	0.015	0.288
		120°	-.055*	0.020	***0.032****
	90°	**120°**	-0.030	0.019	0.419
Triceps muscle activity	**45°**	**90°**	-0.006	0.012	1.000
		120°	-.036*	0.012	***0.015****
	90°	**120°**	-.030*	0.010	***0.020****
CCI	**45°**	**90°**	-0.016	0.035	1.000
		120°	-0.078	0.033	0.076
	90°	**120°**	-0.062	0.026	0.067
RPE	**45°**	**90°**	-1.893*	0.243	***0.000****
		120°	-3.714*	0.293	***0.000****
	90°	**120°**	-1.821*	0.252	***0.000****
**** The mean difference is significant at the .05 level.***					

SUMMARY OF FINDINGS

Athletes exhibited higher biceps activation and lower triceps activation compared to non-athletes during isometric elbow flexion, accompanied by reduced co-contraction and lower perceived exertion, indicating better neuromuscular control. These differences remained consistent across elbow angles, demonstrating adaptation patterns in trained individuals. The absence of interaction effects indicated that, while both groups exhibited similar angle-related changes, the group differences remained constant, suggesting training-induced adaptations in neuromuscular control among athletes.

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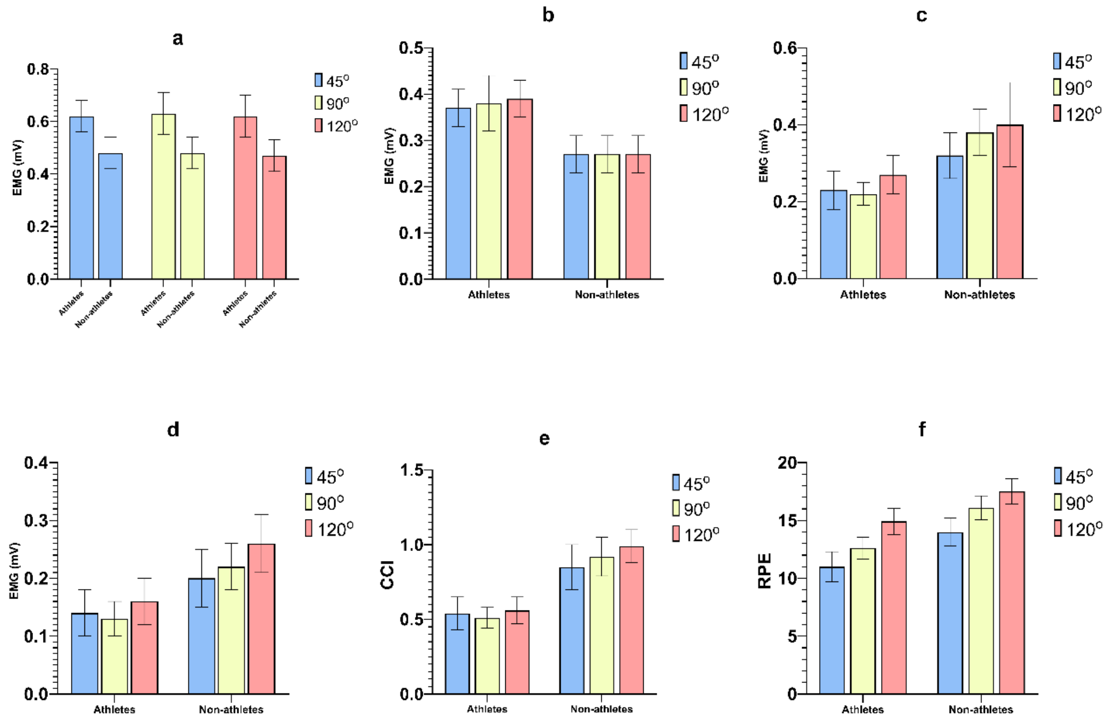

Figure 1: Neuromuscular and perceptual responses during isometric elbow flexion in volleyball players (Athletes) and sedentary adults (non-athletes) at three joint angles (45°, 90°, 120°; blue, yellow, and red bars, respectively). A, Biceps EMGmax; B, Biceps EMG RMS; C, Triceps EMGmax; D, Triceps EMG RMS; E, co-contraction index (CCI); F, rating of perceived exertion (RPE). Bars show group Means ± SDs.

DISCUSSION

This study aimed to compare neuromuscular strategies during sub-maximal isometric elbow flexion in volleyball players and sedentary adults. Three principal findings emerged: (i) athletes showed markedly greater agonist (biceps brachii) activation, (ii) they exhibited lower antagonist (triceps brachii) activation and co-contraction, and (iii) they reported lower ratings of perceived exertion (RPE) at every joint angle tested (45°, 90°, 120°).

ENHANCED AGONIST DRIVE IN TRAINED PARTICIPANTS

The ~50 % higher normalized EMG amplitude observed in athletes (Mean = 0.63 mV vs 0.42 mV) indicates superior neural drive to the prime mover. Recurrent explosive training is known to upregulate descending cortical input and spinal motoneuron excitability, thereby fostering larger motor-unit recruitment and increased firing rates. (Walker, 2021). Our data extend this idea to isometric conditions and moderate force levels, corroborating the broader evidence that sport-specific practice raises agonist EMG across a variety of upper-limb tasks. (HORTOBÁGYI et al., 2021).

REDUCED ANTAGONIST ACTIVITY AND CO-CONTRACTION

Athletes demonstrated ~35 % lower triceps activation (M = 0.25 mV vs 0.38 mV) and a substantially smaller co-contraction index. Similar reductions have been reported in racket-sport athletes during both isokinetic and isometric elbow efforts, suggesting that long-term practice refines reciprocal inhibition pathways and decreases the need for joint-stiffening co-activation (BAZZUCCHI et al., 2008). Lower antagonist engagement minimizes unnecessary opposing torque, improving net torque efficiency and potentially reducing metabolic cost. (HORTOBÁGYI et al., 2021).

JOINT-ANGLE EFFECTS

Across groups, triceps EMG rose at larger elbow angles (120° > 90° > 45°), whereas biceps activation remained stable. This pattern aligns with biomechanical models predicting higher elbow-extension moments when the forearm approaches full flexion, necessitating greater braking from the antagonists. (WALKER, 2021). Crucially, the absence of a Group × Angle interaction indicates that training adaptations are expressed uniformly along the length-tension curve, rather than being angle-specific.

LOWER PERCEIVED EFFORT IN ATHLETES

Athletes rated the task 1–2 points lower on the Borg RPE scale than controls. Resistance-trained individuals typically report diminished RPE at equivalent absolute loads, attributable to both peripheral adaptations (e.g., improved phosphocreatine resynthesis) and central factors such as more economical motor-unit recruitment. (SILVA, 2020). Our findings reinforce the notion that neuromuscular efficiency translates into a lower conscious sense of effort during static contractions.

THEORETICAL IMPLICATIONS

Collectively, these results support the efficiency hypothesis: regular high-velocity strength and skill training foster a motor strategy that maximizes desired torque while suppressing unnecessary antagonist activity. This adaptation likely involves enhanced reciprocal inhibition, corticospinal reweighting, and optimized intermuscular coordination frameworks, as described in contemporary reviews of neuroplasticity. (HORTOBÁGYI et al., 2021).

PRACTICAL APPLICATIONS

Lower antagonist co-activation can enhance force output for a given neural drive, which is advantageous in power-dominated sports such as volleyball. Coaches may therefore incorporate targeted eccentric control and reciprocal facilitation drills to reinforce these patterns. In rehabilitation, monitoring co-contraction indices could serve as a marker of neuromuscular recovery and training progression.

LIMITATIONS AND FUTURE DIRECTIONS

Although surface EMG provides valuable insights, it does not capture the contributions of deep muscles and is influenced by factors such as electrode placement and normalization. The cross-sectional design precludes causal inference; longitudinal training studies are needed to confirm that reduced co-contraction emerges with practice. Finally, extending analyses to dynamic and fatigue-inducing protocols would clarify whether the observed advantages persist under sport-specific conditions.

CONCLUSION

Volleyball players exhibited significantly greater biceps activation, reduced triceps activation, lower co-contraction indices, and a diminished perception of effort during isometric elbow flexion compared to their sedentary peers. These findings suggest that chronic sport-specific training enhances neuromuscular efficiency by amplifying agonist drive and reducing antagonist interference, consistent with adaptations observed in other trained populations. (BAZZUCCHI et al., 2008; HORTOBÁGYI et al., 2021). The resultant improvements in coordination and effort perception may contribute to enhanced performance and a reduced risk of injury. Future work should track these variables longitudinally across different sports and incorporate dynamic tasks to elucidate the scope of training-induced neuromuscular plasticity fully.

STATEMENTS & DECLARATIONS

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CONFLICT OF INTERESTS

The authors state that they have no conflicts of interest, whether financial, non-financial, or otherwise, to disclose.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's initial planning and design. DR and AB obtained the necessary ethical approval. DR and MP were responsible for gathering data, drafting the manuscript, and making revisions. PC handled the statistical analysis, while AB and PC interpreted the data. The final version of the manuscript was reviewed and approved by all authors.

DATA AVAILABILITY

Data is available from the corresponding author on reasonable request.

ETHICS APPROVAL

The Human Ethics Committee of Serampore College, affiliated with the University of Calcutta, approved the study (***Reference No. SC/HEC/2025/P1B, dated 10.02.2025***) in accordance with the Helsinki Declaration of 1975.

CONSENT TO PARTICIPATE

The purpose of the study was thoroughly explained to the participant, and only those who agreed to participate were included in the study after providing written informed consent.

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