How Altruistic Motivation Synchronizes Brain-Muscle Coherence to Enhance Motor Performance

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Abstract

While extrinsic and intrinsic motivation have been well studied, the effects of altruistic motivation on motor performance remain largely unexplored. This study investigates the influence of altruistic motivation on brain–muscle coherence and its effect on improving time to task failure. Thirty-one participants performed two high-intensity isometric grip tasks to failure. The first trial was conducted without any extra motivational incentive, while the second trial was performed under one of three conditions: altruistic, extrinsic, or control. Electroencephalogram (EEG) and electromyogram (EMG) signals were recorded during both trials. Our results demonstrate that only the altruistic group improved their performance from the first to the second trial (68%; $p = 0.004$). The altruistic group exhibited increased EEG–EMG coherence in the alpha and beta bands and reduced delta coherence. These findings suggest that prosocial motivation restructures neural oscillatory activity, optimizing force control and endurance.

Keywords: altruistic motivation; motor performance; EEG-EMG coherence; prosocial behavior; endurance

Introduction

Motivation significantly influences human performance, impacting cognitive, emotional, and physiological states. Traditional models distinguish between intrinsic motivation, which is driven by self-satisfaction, and extrinsic motivation, which is influenced by external rewards [1]. Altruistic motivation, a prosocial driver rooted in social reward circuits, has been linked to enhanced neural synchronization and improved autonomic regulation [2,3]. However, its role in motor control remains largely unexamined.

While intrinsic and extrinsic motivation have been studied extensively in the context of motor learning and effort regulation, especially in sports and rehabilitation [4,5], fewer studies have directly examined how these motivational states shape corticomuscular dynamics. Intrinsic motivation promotes deep task engagement and persistence, while extrinsic rewards can sometimes improve short-term performance at the cost of sustained effort or attentional focus. Altruistic motivation, in contrast, may combine the goal-directed engagement of intrinsic motivation with the social salience of external rewards, thereby recruiting overlapping but distinct neural and physiological pathways. Studies indicate that altruistic motivation can modulate neural activity via increased oxytocin release and heightened parasympathetic activity, potentially promoting emotional stability and cognitive efficiency [6]. This may facilitate a synchronized physiological state that optimizes motor performance in high-demand tasks. Furthermore, brain networks such as the Default Mode Network (DMN), Sensorimotor Network (SMN), and Frontoparietal Network (FPN) are known to interact dynamically under different motivational conditions [7–10].

Furthermore, studies investigating dynamic tasks have shown that the transition into task failure often coincides with distinct changes in EMG power in the sub-100 Hz range, highlighting potential cortical influences on muscle activation [11]. Specifically, increases in the 13–50 Hz bandwidth, sometimes referred to as beta and low-gamma ranges, have been linked to a heightened drive from cortical to spinal circuits, reflecting an adaptive, albeit transient, recruitment strategy to sustain force [12,13]. Wavelet-based analyses are particularly well-suited to capture these time-varying oscillatory components because they allow simultaneous examination of signal amplitude and frequency content [14], even as fatigue sets in [11]. In high-effort tasks, such as isometric or dynamic contractions, wavelet transforms can thus reveal critical patterns in EEG-EMG coherence that conventional methods might mask. This is especially relevant to motor performance and motivation studies, where subtle shifts in oscillatory power could distinguish successful force maintenance from task failure.

Neural synchronization between brain and muscle, often quantified via EEG–EMG coherence, has been shown to reflect both task demands and motivational states [15,16]. For instance, beta-band corticomuscular coherence increases during sustained isometric contractions, especially when attention and effort are high, and declines with fatigue or distraction [17,18]. Motivational framing may thus modulate coherence by influencing the allocation of attentional and cognitive resources. Prior work has found that higher motivation can enhance synchronization between central and peripheral systems, improving force steadiness and endurance [19]. However, most of these studies have focused on extrinsic or intrinsic motivation, leaving open the question

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of how prosocial motivational states influence this neural coupling.

Despite the growing body of research on motivation and neural dynamics, the impact of altruistic motivation on corticomuscular coherence during high-effort task failure tasks remains an open question. Prior research has shown that motivational states modulate attention, emotional arousal, and executive control [20,21], factors that are known to influence cortical oscillations and corticomuscular coupling [22,23]. Altruistic motivation engages distinct neurocognitive circuits involving social cognition, purpose, and intrinsic engagement [24,25], which may promote focused attention and emotional regulation during high-effort tasks. These states can lead to more efficient communication between motor cortices and spinal motor units, observable as changes in brain-muscle coherence patterns [22,23,26]. We therefore hypothesized that altruistic motivation would uniquely influence corticomuscular synchronization, compared to extrinsic or neutral conditions, by modulating coherence in key frequency bands known to support motor execution and control under fatigue.

This study examines how altruistic motivation influences EEG-EMG coherence and task performance during a high-intensity isometric grip task to failure. We hypothesize that prosocial motivation enhances corticomuscular synchronization, improving endurance and motor efficiency.

Methods

Participants

Thirty-one healthy adults (mean age: 30.6 ± 8.2 years; 15 men, 16 women) participated. Inclusion criteria included normal vision, good health, and no neurological disorders. All participants provided informed consent, and the study was approved by the Ethics Committee of Anhembi Morumbi University (CAAE: 67190123.3.0000.5492).

A priori power analysis was conducted using G*Power 3.1.9.7 [27] to determine the appropriate sample size. Assuming a small-to-medium effect size (Cohen’s f = 0.3), an alpha level of 0.05, two repeated measures (pre- and post-intervention), and three between-subject groups, the analysis indicated that a total sample size of 30 participants would be sufficient to achieve 80% statistical power. Our final sample size of 31, therefore, met this requirement.

Task and Experimental Design

Participants were randomly assigned to one of three groups: Altruistic (n = 10), Extrinsic (n = 11), and Neutral (n = 10). Each group performed two trials of an isometric force task to failure with their dominant hands [11,28] at 95% of their maximum voluntary contraction (MVC). Before the second trial, participants received motivation aligned with their group: altruism-based motivation, a tangible reward (chocolate), or no explicit motivation.

For the Altruism group, a video was presented during the final two minutes of a 10-minute rest period. In it, the principal investigator (PI) thanked participants for their involvement and informed them that each second they maintained a force above 95% MVC, a 5 Brazilian reais (5.00 R$) per second donation would be made to a social project aiding underprivileged children. This was followed by a clip of two children from the program requesting participants' help. Participants were not informed of any personal recognition or benefit, and the donation was explicitly framed as benefiting the children only. No feedback or symbolic reinforcement (e.g., praise, badges, names) was provided, minimizing the possibility that the incentive would be perceived as self-serving or reputational.

For the Extrinsic Group, a similar video by the PI informed participants that they would receive a treat for every second their force exceeded the 95% MVC threshold. To ensure equivalency across motivational conditions, the monetary value of the chocolate treats provided in the Extrinsic group matched the donation value used in the Altruistic condition, totaling approximately 5.00 Brazilian reais per second of sustained effort. This parity aimed to isolate the effect of motivational framing, altruistic versus self-reward, while controlling for incentive magnitude. Importantly, due to ethical guidelines enforced by Brazilian research oversight (e.g., National Health Council Resolution CNS 466/2012), financial compensation directly to participants for task performance is prohibited. Thus, we did not include a condition where participants received money for themselves, as such an approach would violate national ethical standards for human subjects research.

The Neutral Group watched a video. At the eighth minute, the PI thanked them and asked them to perform their best in the second trial.

Each participant performed two trials of an isometric grip task using an HD-BTA dynamometer (Vernier Software, USA). They attempted to maintain 95% of their MVC until failure. Visual feedback was provided via a 15.6-inch screen. The total duration (in seconds) for which participants could sustain force levels above the target threshold was measured.

EEG and EMG Data Collection

EEG and EMG signals were recorded at 512 Hz using the iBlue 64 polysomnography system. EEG electrodes followed the 10/20 system, with signals band-pass filtered at 0.1-70 Hz. EMG signals were collected from the dominant hand, band-pass filtered (5-256 Hz), and rectified before wavelet coherence analysis.

Data Analysis

Signal processing was performed using MATLAB (2022a). EEG data were preprocessed using Independent Component Analysis (ICA) for artifact removal. After applying Independent Component Analysis (ICA) for artifact removal [29], cleaned EEG signals were mapped onto five key brain networks: the Default Mode Network (DMN; Fp1, Fp2, P3, P4), involved in the self-referential and resting-state activity;

the Frontoparietal Network (FN; F3, F4, P3, P4), associated with cognitive control and decision-making; the Visual Network (VN; O1, O2, Oz), linked to visual processing; the Attention Network (AN; F7, F8, P3, P4, P7, P8, O1, O2, Oz), which supports attentional control and sensory processing; and the Sensorimotor Network (SN; C3, C4, Cz), governing motor control and sensory integration.

Coherence analyses were then conducted across five EEG frequency bands. Delta (1–4 Hz), Theta (4–8 Hz), Alpha (8–12 Hz), Beta (12–30 Hz) and Gamma (30–80 Hz). Mapping neural signals to these specific networks and frequency bands provides a detailed framework for understanding how different oscillatory dynamics contribute to motor performance, particularly under varying motivational states.

Wavelet coherence between EEG and EMG signals quantified brain-muscle synchronization across these bands (Equation 01, Wang et al., 2022).

$$R_n^2(s,\tau)^{XY} = \frac{\left|S\left(s^{-1}W^{XY}(s,\tau)\right)\right|^2}{S\left(s^{-1}\left|W^X(s,\tau)\right|^2\right).S\left(s^{-1}\left|W^Y(s,\tau)\right|^2\right)} \qquad (1)$$

where $R_n^2(s,\tau)XY$ represents the squared wavelet coherence between signals X and Y for a given scale s and time shift τ; s the scale factor, which represents frequency dilation (a higher scale corresponds to a lower frequency) τ the time shift parameter; $W^{XY}(s,\tau)$ the cross wavelet transform between signals X and Y (it captures the common power and phase between the two signals at each scale and time shift, Chen et al. 2012); $|W^X(s,\tau)|$ the absolute value of the wavelet transform of signal X (representing its power); $|W^Y(s,\tau)|$: The absolute value of the wavelet transform of signal Y; and S is a smoothing operator that has a similar footprint as the Morlet wavelet (it helps in making the coherence measure more robust and less affected by noise).

Statistical Analysis

A mixed linear model (MLM) was first employed to compare measurements between Trials 1 and 2 across three groups (Altruistic, Extrinsic, and Neutral). This model was selected to handle repeated measures of EEG networks, EEG and EMG frequencies, and changes in trial performance while accounting for between-subject variance via random intercepts. Model assumptions were tested with the Shapiro–Wilk procedure for normality of residuals and Levene's test for homogeneity of variances. When normality was violated, we explored a log transformation. If this log-transformed model failed to meet normality criteria or better distributional fit, we used a Gamma generalized linear mixed model (Gamma GLMM) with a log link, given the strictly positive nature of coherence measures. In all instances, Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and log-likelihood values helped us confirm model appropriateness and parsimony.

For post-hoc analysis of significant factors and interactions, we computed estimated marginal means with Tukey's adjustments for multiple comparisons. Where higher-order interactions (e.g., four-way terms) showed no significance or limited contribution, we performed a model reduction by excluding the noncontributory factor and rechecking whether the remaining interactions improved model fit. This stepwise reduction limited overfitting and heightened the detection of meaningful changes in our physiological measures. Statistical significance was maintained at $p < 0.05$. Data are presented as mean ± standard deviation (SD).

We conducted a correlation analysis to explore how coherence measures might predict improvements in force endurance (time above 95% maximum voluntary contraction). We considered each post-hoc variable that reached significance in the non-reduced models. We computed Pearson's r correlations between changes in these measures and the change in time above 95% MVC from Trial 1 to Trial 2. The seven strongest correlates were then entered into a stepwise multiple regression (stepAIC in R) to identify the top predictors of performance. All analyses were executed in R (version 4.4.1), and figures were generated through ggplot2 and gridExtra.

Results

Force Performance

A mixed linear model was used to assess changes in time above 95% MVC (dependent variable) across the three groups (Altruistic, Extrinsic, Neutral) and intervention periods (Pre, Post), with random intercepts for participants. The final model had logLik = –196.25, AIC = 408.51, and BIC = 425.26, indicating an acceptable fit.

An ANOVA on this model yielded a significant Group × Intervention interaction (F(2,27)=3.41, p = 0.0476). Post-hoc comparisons showed that only the Altruistic Group significantly improved its time maintaining force above 95% MVC (estimate = 6.57 s, SE = 2.08, t=3.17, p = 0.004), moving from 9.11± 8.12 s to 15.29±10.39 s. The Extrinsic and Neutral groups did not exhibit statistically significant changes. Figure 1 contains violin and box plots illustrating these differences pre- and post-intervention.

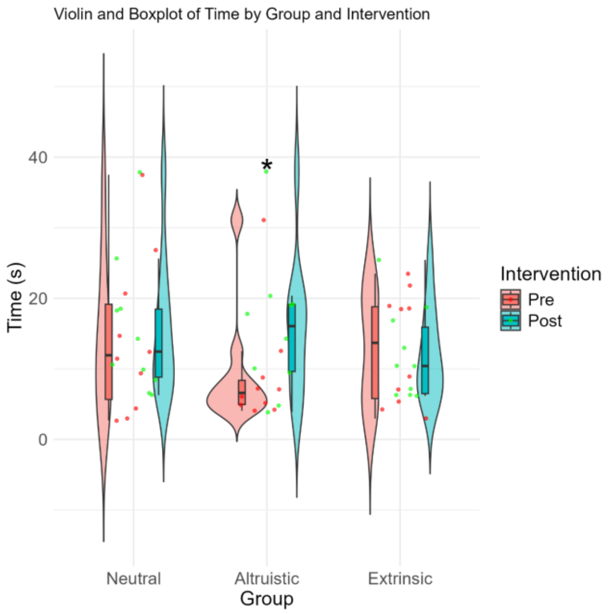

Figure 1: Time maintaining force above 95% MVC (s) per group, before and after intervention.

EEG-EMG Coherence

The initial Gamma GLMM (logLik = 1675.41, AIC = -3166.82, BIC = -2721.98) that included Network yielded no significant four-way interaction (Intervention × Group × Bands × Network). After removing Network, the final model (logLik = 2221.24, AIC = -4378.48, BIC = -4214.55) indicated a significant Intervention × Group × Bands term (LRT = 103.46, $p < 0.001$, generalized η^2 (based on a linear model) = 0.067). Post-hoc pairwise comparisons showed substantial pre-post changes in Delta, Alpha, and Beta coherence, with the altruistic and extrinsic groups demonstrating opposite directions of effect in the Delta band. Specifically: the altruistic group exhibited a marked decrease in delta coherence (ratio = 1.2665, z = 8.54, $p < 0.001$) but increases in alpha (ratio = 0.9270, z = –2.74, p = 0.006) and Beta (ratio = 0.9409, z = –2.21, p = 0.0273). The extrinsic group, in contrast, showed an increase in delta coherence (ratio = 0.8611, z = –5.66, $p < 0.001$). The neutral group showed a milder decrease in delta (ratio = 1.0604, z = 2.12, p = 0.034). Figure 2 displays these EEG–EMG coherence shifts across five frequency bands, underscoring that Delta range changes were notably distinct between the altruistic and extrinsic groups. At the same time, Alpha and Beta bands also contributed to the altruistic group's overall pattern. Figure 3 further illustrates these findings by plotting the estimated marginal means and confidence intervals for each group across delta, alpha, and beta bands. This offers a visual breakdown of the interaction effects and makes the coherence dynamics more interpretable.

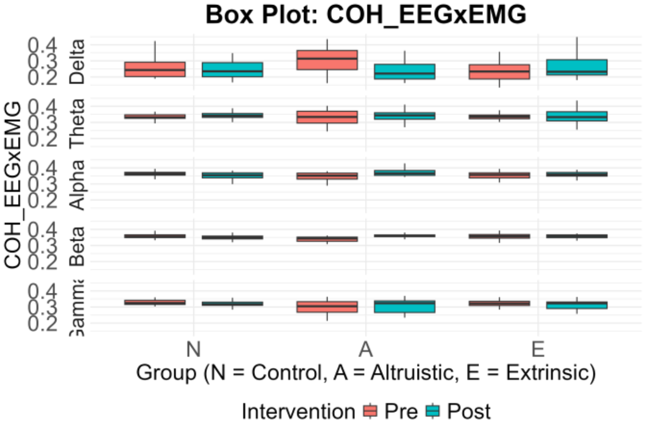

Figure 2: EEG–EMG coherence for each EEG band, showing group differences from pre to post.

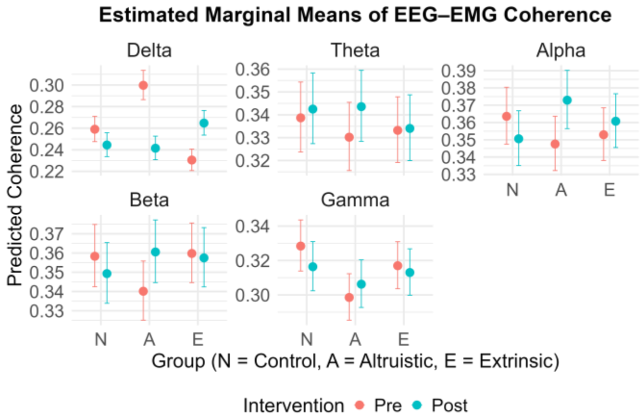

Figure 3: Estimated marginal means and 95% confidence intervals for EEG–EMG wavelet coherence showing group differences from pre to post.

Correlation Analysis

Correlation analyses examined how changes in coherence variables related to performance (time above 95% MVC). Although Networks did not emerge as a significant factor in the GLMM, post-hoc tests suggested that some networks might still contribute unique variance. The strongest correlations were found in the Delta band for the VN (visuomotor) network (R = -0.735, $p < 0.001$) and for the SM (sensorimotor) network (R = -0.733, $p < 0.001$). See Figure 4 for scatter plots.

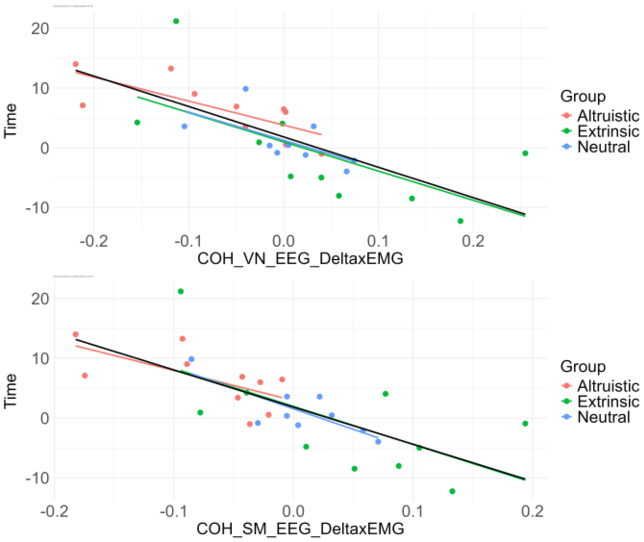

Figure 4: Scatter plot and regression lines for each group for with the strongest correlation of EMG and Delta band for the VN (visuomotor) network (R = -0.735, $p < 0.001$) and for SM (sensorimotor) network (R = -0.733, $p < 0.001$) EEG.

Furthermore, multiple regression analysis with the seven most correlated variables suggests that the alpha band coherence from SN was the most important variable. Model results were $F(5,23) = 9.422$, with Adjusted $R^2 = 0.601$ and $p < 0.001$ (Figure 5).

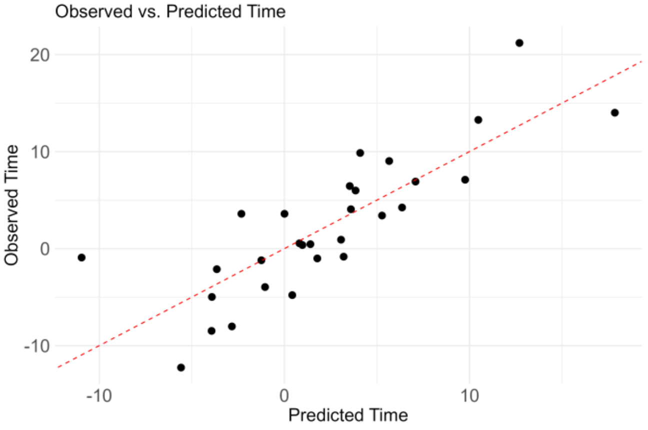

Figure 5: Scatter plot of the multivariate stepwise model results (adjusted $R^2 = 0.601$, $p < 0.001$). Sensorimotor network alpha band coherence with EMG was the most significant variable explaining the improvement in time from trial 1 to trial 2.

Discussion

This study examined how altruistic motivation influences EEG–EMG coherence and task performance during an isometric grip task performed to failure at 95% MVC. Thirty-one healthy adults participated in two trials, and we measured the time they could sustain the task and their EEG–EMG wavelet coherence. Participants received one of three motivational conditions between trials: altruistic, extrinsic, or neutral. Our main findings were: (a) only participants in the altruistic group demonstrated a significant and relevant (approximately 68%) increase in time to task failure in the second trial compared to the first; (b) the altruistic group exhibited lower delta and higher alpha and beta corticomuscular coherence; and (c) correlation analysis revealed that lower delta and higher alpha coherence were significantly associated with improvements in time to failure from trial 1 to trial 2.

Importantly, our results showed that altruistic motivation decreased delta coherence while increasing alpha and beta coherence between EEG and EMG signals. These effects align with theoretical predictions about how motivational framing can modulate corticomuscular communication during high-effort tasks.

In the context of brain–muscle coherence, delta-band synchronization is often interpreted as a marker of cognitive interference, low-frequency neural “noise,” or compensatory effort, particularly under fatigue or divided attention [16,30,31]. Thus, the reduction in delta coherence among altruistic participants likely reflects reduced neural interference and enhanced attentional focus, enabling more stable motor output.

Alpha-band coherence, which traditionally relates to a relaxed wakeful state and inhibition of irrelevant sensory processing [32,33], also plays a critical role in sensorimotor gating and attentional regulation during motor tasks [15]. The increased alpha coherence in the altruistic group suggests improved focus and top-down suppression of irrelevant inputs, contributing to more consistent force production.

Perhaps most critically, beta coherence is a robust indicator of effective corticospinal drive, especially in tasks requiring sustained force like isometric contractions [13,18,34]. Beta-band activity is associated with motor planning, sensorimotor integration, and execution, and its enhancement reflects precise, goal-directed engagement of the neuromuscular system. It may also relate to how the central nervous system manages fatigue [11]. The altruistic group’s increase in beta coherence may indicate stronger top-down motor control, likely driven by a socially meaningful motivational state that engages attention and executive resources more effectively than self-directed rewards.

These oscillatory changes suggest a neurophysiological mechanism whereby prosocial motivation reorganizes brain–muscle synchronization, allowing participants to resist fatigue better and maintain force output. This pattern aligns with the idea that altruistic motivation may reduce internal cognitive noise while amplifying the efficiency of motor-related communication pathways, culminating in the observed improvements in performance.

Our findings extend prior research on neural synchronization under effortful conditions by demonstrating that motivational framing alone, without changes in physical demands, can alter corticomuscular coherence. This aligns with studies showing that attention, mental fatigue, and psychological engagement affect EEG–EMG [15]. Altruistic motivation may act as a cognitive-emotional amplifier, increasing the alignment of central and peripheral systems through mechanisms like those observed under high-incentive or highly self-relevant tasks.

From a cognitive science perspective, motivation is not merely an external driver but a key component in shaping cognitive architectures and performance [1]. Altruistic motivation's distinct effects on neural oscillations speak to the interplay between social cognition, emotional states, and sensorimotor control. Our results suggest that the "cost function" in computational terms might be differentially weighted under altruistic motivation, culminating in more persistent or efficient force output.

Additionally, altruistic motivation could influence how the cognitive system allocates attention to the motor task. In extrinsic conditions, attention may be split between the reward and the physical effort, generating cognitive load and potentially elevating delta coherence, which can harm sustained performance. By contrast, altruism may unify participants' attention around a socially meaningful goal, creating what some cognitive models describe as a more streamlined or optimized attention schema [35,36].

In clinical rehabilitation, framing exercises in an altruistic context, such as performing movements with the knowledge that each repetition contributes to a charitable cause, may enhance patient engagement and adherence. Motivational resilience often represents a bottleneck in rehabilitation programs; thus, harnessing prosocial incentives could mitigate dropout rates and accelerate progress [2]. Furthermore, a prosocial motivational climate within teams may foster better synchronization and cooperation in elite sports and high-performance settings, translating into improved individual and collective performance. While extrinsic rewards are commonly employed, the findings suggest that altruism-driven incentives could offer an alternative or complementary approach with unique neurophysiological benefits.

Altruistic motivation is partly rooted in social and affective neuroscience, involving empathy, compassion, and reward circuits [2,3]. The observed decreases in delta and increases in alpha and beta coherence may align with the neuroendocrine effects of oxytocin or other prosocial neurochemicals, which have been associated with heightened trust and cooperation. Future fMRI or magnetoencephalography (MEG) studies could pinpoint more precisely which structures (e.g., anterior insula, medial prefrontal cortex) are driving these changes in cortical oscillatory activity. Such work could significantly enhance our understanding of how motivational states rooted in social connectedness translate into concrete motor improvements.

While our findings highlight the performance-enhancing effects of altruistic motivation, it is essential to acknowledge that the type of altruism investigated here represents a structured and goal-directed form, namely, contributing to a charitable cause in response to an explicit appeal. This form of instrumental altruism differs from more spontaneous or unrewarded acts of kindness that may emerge without prompting or external framing. In real-world contexts, altruism is multifaceted: it can range from reflexive helping to deliberative prosocial choices shaped by social norms and context [25,37]. Future research should explore whether spontaneous, unconditioned altruistic acts, particularly those occurring without external cues or incentives, elicit similar patterns of corticomuscular synchronization and performance benefits.

Limitations and Future Directions

While the study sought to isolate altruistic motivation from extrinsic reward, it is possible that some participants derived internal satisfaction or social validation from helping others. This highlights a broader challenge in motivation research: altruistic behavior may produce emotional or reputational rewards, even when not directly incentivized. However, our design explicitly framed the donation as benefiting others without offering the participant feedback, recognition, or personal gain. Future work might use additional tools, such as social desirability scales or post-task interviews, to assess whether perceived self-benefit influences motivational framing.

Additionally, the study demonstrated significant and interpretable effects despite the relatively small sample size (n = 31), but the between-subjects design introduced some limitations regarding statistical power. We acknowledge that larger sample sizes are generally preferable, and a within-subject design might have offered increased sensitivity. However, due to potential learning and fatigue effects inherent in repeated grip-to-failure tasks, a within-subjects motivational manipulation would have introduced confounding order effects. It is also important to note that, while the monetary value of rewards was matched across groups, we could not include a direct monetary reward condition due to ethical restrictions in Brazil that prohibit paying participants for performance. This differs from standard research practices in countries like the United States and limits our ability to directly test whether self-directed financial rewards would produce effects comparable to altruistic motivation. Nevertheless, the matched value of extrinsic (chocolate) and altruistic (donation) incentives suggests that the observed differences are more likely driven by the motivation's nature rather than the incentive's size.

Finally, while this study focused on a structured form of altruistic motivation, supporting a charitable cause following an explicit appeal, future research should explore more nuanced and ecologically valid expressions of prosocial behavior. For instance, designs could incorporate spontaneous helping behaviors, anonymous giving, or effort without acknowledgment, which may resemble naturally occurring altruism more closely. Including these conditions would allow researchers to disentangle instrumental prosocial from more instinctive or morally driven actions. We recommend future studies investigate how these variants affect brain–muscle coherence and motor performance, possibly revealing different neural signatures and motivational effects.

Conclusion

Our results underscore the decisive role that altruistic motivation can play in reorganizing corticomuscular coherence to enhance motor performance. Unlike extrinsic motivation, which may inadvertently elevate cognitive load or anxiety, altruistic drives appear to optimize the neural circuitry responsible for force control and sustained performance. These findings illuminate new avenues for applying prosocial incentives in fields as diverse as rehabilitation, sports, and performance psychology, offering a promising strategy for improving compliance, endurance, and overall success.

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