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BEYOND BAR CHARTS: A COMPARATIVE ANALYSIS OF LINEAR MIXED-EFFECT MODELS AND ANOVA FOR EVALUATING EXOSKELETON PERFORMANCE

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ABSTRACT

This study introduces Linear Mixed-effect Models (LMM) as an advanced alternative to ANOVA for evaluating exoskeleton performance in in all fields of application. Comparing these approaches using electromyography data from erector spinae muscle, the study reveals LMM's ability to detect even small differences in measurement parameters. The discussion highlights LMM's capacity to incorporate underlying grouping factors and hereby enhancing statistical significance.

Keywords: Exoskeletons, Linear Mixed-effect Models, ANOVA, Statistical comparison, EMG

1. INTRODUCTION

Exoskeleton technology is gaining prominence for its potential to reduce musculoskeletal disorder risks in various work scenarios. While its efficacy is supported by numerous studies, the typical practice of presenting results using bar charts and perform statistical analysis with analysis of variance (ANOVA) has limitations. Linear Mixed-effect Models (LMM), widely used in other disciplines [1], are rarely employed in exoskeleton experiments [2]. However, LMM's strengths, especially in handling repeated and grouped measurements, offer the promise of more accurate outcomes in exoskeleton studies, even in scenarios with missing data or non-normally distributed data [3], e.g EMG data. This study aims to bridge the gap by exploring LMM's applicability in exoskeleton research, using real data from lifting experiments to demonstrate its superiority over traditional ANOVA approaches and advocates for a better presentation of the results in publication of exoskeletons [4, 5].

2. MATERIALS AND METHODS

The study's methodology involved a dataset recorded from lifting tests performed with a passive exoskeleton. Ten test subjects engaged in 36 lifting-lowering cycles under two conditions: lifting a 10 kg weight without an exoskeleton (10KgNoExo) and lifting the same weight with an exoskeleton (10KgExo). Surface electromyography data of the erector spinae muscle were collected. The beginning and end of each repetition were tracked, and an EMG peak and EMG mean value were calculated for each repetition. Importantly, the collected data did not conform to a normal distribution according to the One-sample Kolmogorov-Smirnov test.

For the traditional ANOVA approach, the mean and standard deviation for the two conditions were computed over all repetitions. Due to the non-normal distribution, a Kruskal-Wallis post-hoc test (KW-test) was employed for significance testing. In contrast, the LMM approach began with a base model and iteratively extended it with plausible fixed effects, assessing model fit using the Theoretical Likelihood Ratio Test (Matlab function “compare”). The best fit was achieved with the fixed effects *presence of an exoskeleton* and *lifting direction* (up or d own), while the *subjects* were treated as random effects.

3. RESULTS AND DISCUSSION

The comparison between the two statistical approaches revealed a general accordance in the outcomes, while also highlighting nuanced differences. Notably, the LMM exhibited a more pronounced reduction in the observed effects compared to the traditional ANOVA.

Figure 1 presents the comparison of EMG-peak values obtained through both methods. Both, ANOVA and LMM, demonstrate significant differences between the two states. However, the effect's magnitude, as indicated by the reduction, was slightly more prominent when employing LMM. The presentation with swarm plot and confidence interval is in accordance with the recommendations for a conclusive presentation of the results [4, 5]. From the plot, the non-normal distribution of the data and the small number of outliers can be observed.

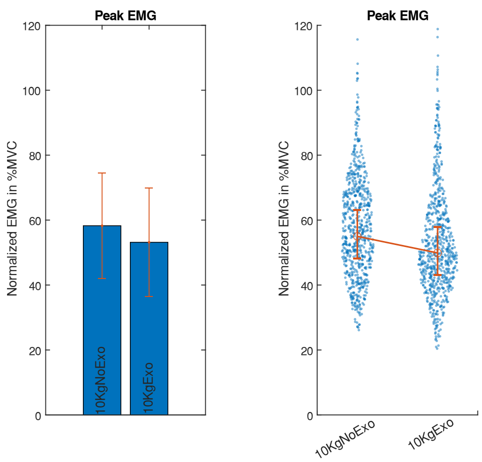

Figure 1: left side: Bar chart with mean an SD, EMG reduction of 8,75 %; Right side: 95 % LMM confidence interval, EMG reduction of 9,28 %.

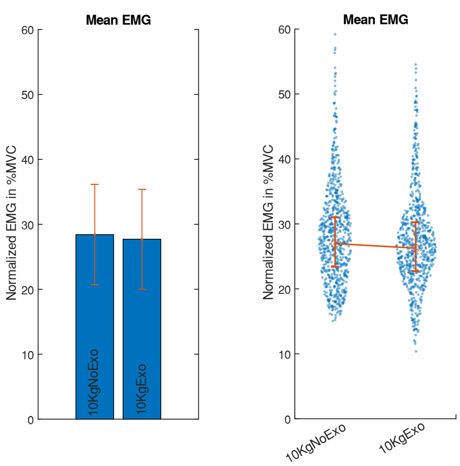

Figure 2: left side: Bar chart with mean an SD, EMG reduction of 2,46 %; Right side: 95 % LMM confidence interval, EMG reduction of 2,6 %.

In figure 2 the methodological differences are more evident. EMG-mean values for the two conditions are illustrated. In the experimental data, these differ only very slightly from each other. While the two methods calculate comparable reductions in EMG-mean values, the ANOVA nonparametric significance test failed to detect a significant difference (p=0,0598) between the two states adopting the established significance level of p ≤ 0,05. In contrast, the LMM indicates a significant difference (p=0,002) between the two conditions and a higher magnitude of the reduction. The outcomes emphasized the benefit of utilizing LMM, providing a broader viewpoint on observed effects by uncovering concealed meaningful distinctions. To illustrate, the model revealed variances between the lifting and lowering stages of the task cycle.

4. CONCLUSION

In conclusion, this work introduces and demonstrates the application of Linear Mixed-effect Models as an advanced statistical method for evaluating EMG data from exoskeleton lifting tasks. However, this can be extended to all other measured metrices in different test procedures. The comparison with the traditional ANOVA approach emphasizes the potential benefits of adopting LMM for a more nuanced understanding of the effects of exoskeletons on human performance. However, LMM is not a miracle cure and cannot detect significance where none exists. Even without using LMM presentation of finding from experiments can be easily improved and we advocate for it. Bar charts should not be used and instead swarm plots or box plots should be used. These have a significantly higher informative value and are state-of-the-art. This work contributes to expanding the methodological toolkit in exoskeleton research, ultimately advancing the comprehension of human-exoskeleton interactions and their implications across various contexts.

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