ALTERATIONS IN MUSCLE SYNERGIES IN PATIENTS WITH KNEE OSTEOARTHRITIS DURING LEVEL- AND DOWNHILL WALKING

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In this study, the effects of knee osteoarthritis (KOA) on muscle synergy composition during locomotion tasks were investigated. Utilizing non-negative matrix factorization on surface electromyography data from 37 participants, analyses of muscle synergies in both level walking and ramp descent in KOA patients and age-matched controls were conducted. It could be shown that KOA affects muscle synergies in the affected limb during level walking, where a merge of synergies during late swing and early stance phases is observed. A similar effect was observed in ramp descent for the affected and unaffected limb. In this study, the impact of KOA on muscular coordination across locomotion tasks is depicted, and it is suggested that muscle synergy analysis can serve as a useful biomarker, e.g. in the assessment of therapeutical interventions.

KEYWORDS: locomotion, hiking, motor control, non-negative matrix factorization

INTRODUCTION: Knee osteoarthritis (KOA) is a prevalent and severe condition with complex effects on human locomotion. It has been shown that light to moderate sports-related activities such as walking and hiking can have a positive effect on pain reduction and joint functionality (Roddy et al., 2005). Understanding changes in neuromuscular organization in the presence of pathologies during such activities can help deepen the understanding of pathomechanisms, and might serve as biomarkers for early detection of a pathology and evaluation of therapeutical interventions. With this objective, several groups applied non-negative matrix factorization (NNMF) on surface electromyography data (sEMG) of locomotion trials, aiming for the extraction of muscle synergies (Santuz et al., 2017). NNMF is a computational technique that is used to decompose a given non-negative matrix (in this context sEMG time series data) into two lower-rank non-negative matrices, which in this context are muscle weightings and temporal activation patterns. Identifying these grouped weightings and activation patterns is the main concept behind muscle synergy analysis. These groups, referred to as synergies, are assumed to reflect an organizational unit within the central nervous system (CNS) during movements (Cheung et al., 2005). The number and composition of synergies has been linked to levels of pain and clinical performance, where a higher number of synergies was associated with better performance and lower levels of pain (Ardestani et al., 2017). Alterations in muscle synergies have been reported for patients after a stroke, total knee arthroplasty or ruptures of the anterior cruciate ligament, and recently for patients with KOA (Casto & Boyer, 2018; Kubota et al., 2023). In level walking, it was reported that two synergies which showed peak activity in either late swing or early stance phase in a healthy group was merged into a single one in the KOA group. This merged synergy showed a longer activation period and a higher number of co-contributors (Kubota et al. 2023). It remains unclear whether the altered activation pattern is specific to the affected limb or represents a broader change within the CNS. Also, no study has yet investigated muscle synergies during downhill walking in patients with KOA, which is a physically more demanding task than level walking for patients with pathological knees (Chen Wen et al., 2022). This study aims to find whether changes in muscle synergy composition related to KOA are observable in the unaffected limb, and whether alterations observed in level walking apply in downhill walking too, which are common tasks in leisure sports like hiking and mountaineering.

METHODS: A total of 37 participants, consisting of the groups KOA (n = 19, 10F : 9M, 63.1 ± 8.3 yrs; 173.2 ± 0.1 cm; 79.3 ± 11.5 kg) and CTRL (n = 18, 9F : 9M, 64.4 ± 7.6 yrs, 170.2 ± 0.1 cm, 71.6 ± 10.9 kg) each performed 10 trials of ramp descent (12°) and overground walking.

From each Trial, a minimum of two complete gait cycles were extracted per side, resulting in a total of min. 80 gait cycles per participant. Both tasks were performed at self-selected speed. 14-Channel sEMG at 1000 Hz (Myon 320, Schwarzenberg, Switzerland) was used to record 7 muscles per leg (VL = vastus lateralis, VM = vastus medialis, ST = semitendinosus, BF = biceps femoris, TA = tibialis anterior, FL = fibularis longus, SO = soleus). Marker-based motion capturing at 200 Hz (Qualisys AB, Gothenburg, Sweden) and force plates at 1000 Hz (Kistler, Winterthur, Switzerland) embedded in the ground and ramp were used for detection of the gait events heel strike (HS) and toe off (TO). After assessment of the raw sEMG data through visual inspection, trials were concatenated per subject and task. Subsequently, the sEMG data was demeaned, and filtered (high-pass, cut-off frequency 50 Hz, fourth order; full wave rectified; low-pass, cut-off frequency 20 Hz, fourth order, Santuz et al., 2017). To avoid boundary effects during filtering, the first and last gait cycles were duplicated prior to filtering, and the duplicates were discarded after filtering. Amplitudes were normalized to the maximum value of each subject per activity. The data were time-normalized to 200 data points, assigning 100 frames to the stance phase, and 100 frames to the swing phase (Santuz et al., 2018b). NNMF was used to extract muscle synergy weights and activation patterns without predefining the factorization rank. The factorization rank incremented starting from 1 and converged when the change in R^2 between the original and reconstructed EMG data was smaller than 0.01% over the last 20 iterations (Cheung et al., 2005). The subject-specific synergies were classified through k-means clustering using the Hartigan-Wong algorithm independently for each group, task, and side. While in the CTRL group left and right side were processed individually, in the KOA group sides were categorized in affected / unaffected and processed individually. For statistical analysis of muscle weights between sides and groups one-way analyses of variance (ANOVAs) were carried out, which in case of statistical significance were followed by post-hoc comparisons through pairwise t-tests with Benjamini-Hochberg adjusted p-values. For all muscle weightings that showed significant differences between sides in post-hoc testing, effect sizes (ES, Cohen's d) were calculated. An alpha level of $p < .05$ was considered to determine statistical significance for all tests. All steps related to sEMG-processing and statistics were carried out in R (version 4.3.0, R Foundation for Statistical Computing, Vienna, Austria) including functions based on the package 'musclesyneRgies v1.2.5' (Santuz, 2022).

RESULTS: For level walking, four classifiable synergies were observed in the CTRL group's left and right legs (Fig. 1).

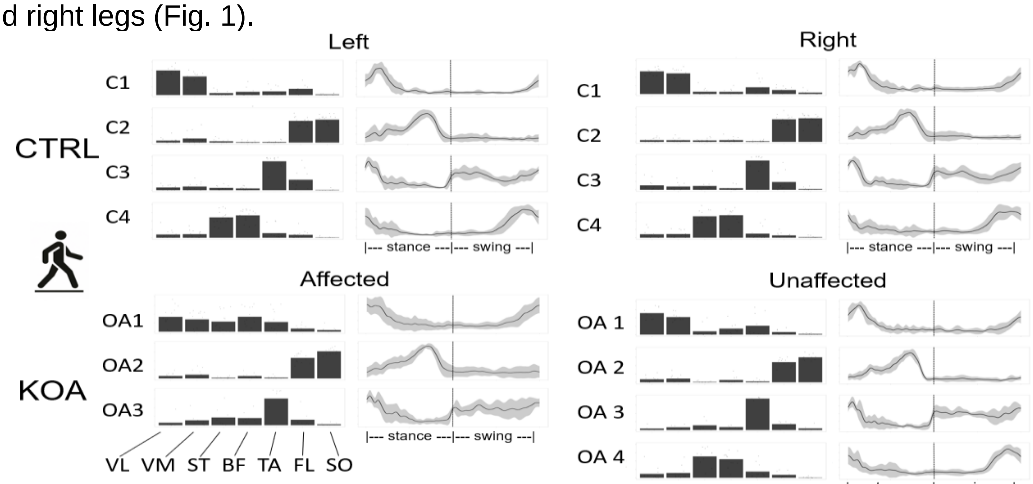

Figure 1: Classified muscle synergies of CTRL and KOA group during level walking. Each classified synergy consists of its mean muscle weightings (bar plots) and synergy activation profiles (line plots, mean & SD), which range from 0 to 1. Vertical lines indicate TO. Four identical synergies were classified in each leg for the CTRL group and KOA unaffected leg, whereas three synergies were identified in the KOA affected leg.

In KOA, four classifiable synergies were observed in the unaffected side, and three in the affected side. Between the unaffected side and CTRL group, no significant differences in muscle weightings were observed for all synergies. In the affected side's synergy OA1, a significant increase of BF (ES = 1.19) and ST (ES = 0.88) contribution along with a decrease of VL (ES = -1.08) and VM (ES = -0.99) contribution was observed compared to the unaffected side. No differences in muscle weightings were observed in synergies OA2 and OA3. For ramp descent, three classifiable synergies were observed in the CTRL group on left and right side (Fig. 2). One-way ANOVA revealed no significant differences across all synergies between left and right leg in CTRL. In KOA, two classifiable synergies were detected for the affected and unaffected leg. One-way ANOVA showed no significant differences in weightings between affected and unaffected side in both synergies in the KOA group. Compared to C2, an increased weighting of TA in synergy OA2 was observed (ES = 0.66).

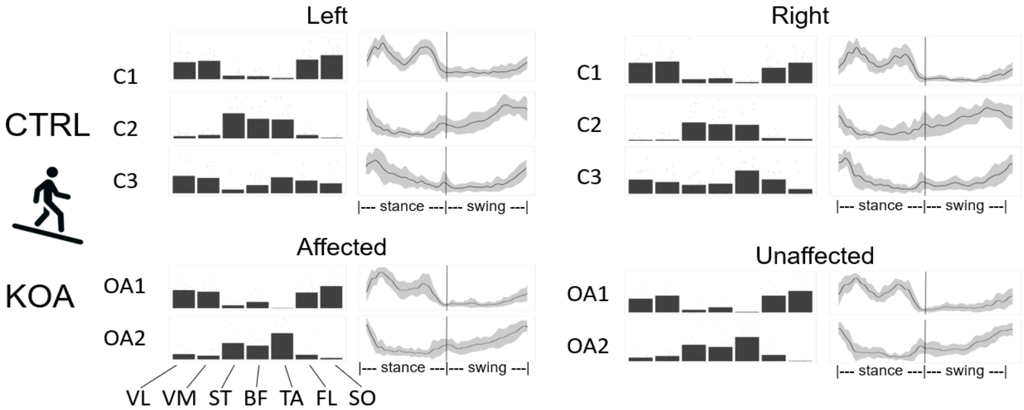

Figure 2: Classified muscle synergies of CTRL and KOA group during ramp descent. Three identical synergies were identified in CTRL, and two in KOA affected and unaffected. Synergy OA 2 shows increased TA contribution, indicating a merging of synergies C2 & C3.

DISCUSSION: The muscle synergies observed in CTRL during level walking support what has been reported in recent literature: In four classified synergies, each synergy is dominated by one muscle group and shows a distinct activation peak (Casto & Boyer, 2018, Rao et al.,2023). In synergy C1, the knee extensors VL and VM show highest contribution, while the activation patterns peaks at loading response during early stance phase. Synergy C2 is characterized by plantar flexor contribution (FL & SO) during terminal stance. Synergy C3 includes predominantly dorsal flexor (TA) contribution during swing phase and heel strike, and synergy C4 involves knee flexor (ST & BF) contribution during mid- and terminal swing. The unaffected side in the KOA group exhibited characteristics identical to those of the CTRL group across all synergies. The affected side differed in two ways: Firstly, only three synergies were classified. In several publications, a decrease in synergy number during identical tasks was linked to a decrease in clinical performance and interpreted as a reduction of neuromuscular flexibility (Ardestani et al., 2017). Secondly, knee flexor contribution in synergy OA1 increased, together with an earlier onset of the corresponding activation pattern. This can be interpreted as a merging of the synergies C1 and C4 for the affected side of the KOA group, which supports recent findings (Kubota et al. 2023). This indicates a certain side-specificity and asymmetry of the modular organization of muscle synergies within the CNS. During ramp descent, less synergies were classified compared to level walking for both groups on both limbs. In CTRL, synergy C1 is characterized by knee extensor and plantar flexor contribution, with peak activity at loading response and terminal stance. Compared to level walking, this can be interpreted as a merge of level walking synergies C1 & C2, which might in part explain the overall reduced number of classified synergies in ramp descent. Synergy C2 in ramp descent contains knee flexor and TA contribution during late swing phase, which again can be seen as a merge of the level walking synergies C3 & C4. Synergy C3 in ramp descent contains co-contributions from various muscle groups, however the peaks during HS and TO indicate a similarity to level walking synergy C3, which is characterized by its TA contribution. In the KOA group, only two synergies were classified per limb. The significant increase in TA contribution in synergy OA2 compared to CTRL indicates a merging of ramp descent synergies C2 & C3. As these synergies show highest activity during late swing and early stance phase in CTRL, it might be comparable to the merging observed during level walking. Interestingly, this is observable symmetrically, although KOA group showed asymmetry in synergy composition during level walking. Given the physically more strenuous task, this might be the result of an overarching compensation strategy or general insecurity during ramp descent in the KOA group. As the total number of synergies has been linked to neuromuscular flexibility by Ardestani and colleagues (2017), the differences in synergy composition observed in this study imply a challenge for KOA patients to adapt to changes in movement requirements during leisure sports. These changes might be due to varying surface conditions and angles during hiking and trekking.

CONCLUSION: In this study, we were able to reveal effects of KOA on muscle synergy composition during locomotion tasks common in recreational sports, e.g. trekking. These included a merging of synergies active during late swing- and early stance phase. This indicates that the impact of KOA neuromuscular organization follows a similar pattern across locomotion tasks. Additionally, muscle synergy analysis appears to be able to serve as a valuable tool for quantifying effectiveness of interventions on neuromuscular level for KOA patients, such as sports therapy and exercise protocols. Due to the relatively low cost of sEMG systems, this can be useful for researchers, practitioners and sports therapists alike.

REFERENCES

Ardestani MM, Malloy P, Nam D, Rosenberg AG, Wimmer MA. 2017. TKA patients with unsatisfying knee function show changes in neuromotor synergy pattern but not joint biomechanics. Journal of Electromyography and Kinesiology 37:90–100. DOI: https://doi.org/10.1016/j.jelekin.2017.09.006

Casto, E. M., & Boyer, K. A. (2018). Altered muscle synergies during gait in individuals with knee osteoarthritis. *Osteoarthritis and Cartilage*, *26*, S381–S382. https://doi.org/10.1016/j.joca.2018.02.746

Chen Wen, Harold E. Cates, Joshua T. Weinhandl, Scott E. Crouter, Songning Zhang: Knee biomechanics of patients with total knee replacement during downhill walking on different slopes; Journal of Sport and Health Science, Volume 11, Issue 1, 2022, https://doi.org/10.1016/j.jshs.2021.01.009

V. C.-K. Cheung, A. D'Avella, M. C. Tresch and E. Bizzi, Central and sensory contributions to the activation and organization of muscle synergies during natural motor behaviors, J. Neurosci. 25(27) (2005) 6419–6434

Kubota, K., Hanawa, H., Yokoyama, M., Kita, S., Hirata, K., Fujino, T., Kokubun, T., Ishibashi, T., & Kanemura, N. (2021). Usefulness of Muscle Synergy Analysis in Individuals With Knee Osteoarthritis During Gait. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *29*, 239–248. https://doi.org/10.1109/TNSRE.2020.3043831

Rabbi, M. F., Pizzolato, C., Lloyd, D. G., Carty, C. P., Devaprakash, D., & Diamond, L. E. (2020). Non-negative matrix factorisation is the most appropriate method for extraction of muscle synergies in walking and running. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-65257-w

Rao, L., Horn, N., Meister, N., Preiss, S., Taylor, W. R., Santuz, A., & Schütz, P. (2023). Comparable in vivo joint kinematics between self-reported stable and unstable knees after TKA can be explained by muscular adaptation strategies: A retrospective observational study. *eLife*, *12*, e85136. https://doi.org/10.7554/eLife.85136

Roddy E, Zhang W, Doherty M. Aerobic walking or strengthening exercise for osteoarthritis of the knee? A systematic review. Ann Rheum Dis. 2005;64:544–8.

Santuz, A., Ekizos, A., Janshen, L., Baltzopoulos, V., & Arampatzis, A. (2017). On the Methodological Implications of Extracting Muscle Synergies from Human Locomotion. *International Journal of Neural Systems*, *27*(05), 1750007. https://doi.org/10.1142/S0129065717500071

Santuz A, Ekizos A, Janshen L, Mersmann F, Bohm S, Baltzopoulos V, Arampatzis A. 2018b. Modular control of human movement during running: an open access data set. Frontiers in Physiology 9:1509. DOI: https://doi. org/10.3389/fphys.2018.01509

Santuz A. 2022. MusclesyneRgies: factorization of electromyographic data in R with sensible defaults. Journal of Open Source Software 7:4439. DOI: https://doi.org/10.21105/joss.04439