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# Effects of ankle stiffness on daily-life activities

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**Efectos de la rigidez del tobillo en actividades de la vida diaria.**

**Resumen**

Realizar actividades básicas de la vida diaria (ABVDs) es fundamental para mantener la independencia personal. Para ello, se requiere una coordinación adecuada entre las articulaciones y un control voluntario del movimiento, que suelen verse limitados en personas con trastornos neurológicos y motores. Las órtesis de tobillo-pie (AFOs) se usan para facilitar el movimiento del tobillo y mejorar la movilidad. Un aspecto clave de estos dispositivos es la rigidez con la que están configurados, la cual influye significativamente en la ejecución de la actividad. Este estudio analiza los efectos de distintas condiciones de rigidez del tobillo durante ABVDs. Cinco sujetos sanos utilizaron la órtesis inGAIT-VSO y realizaron ABVDs en cuatro condiciones diferentes (Baja, Media, Alta y Sin rigidez). Los resultados mostraron que aumentar la rigidez reduce el rango de movimiento (ROM) e influye en la actividad muscular, con diferencias entre actividades. Estas observaciones pueden proporcionar información relevante sobre el comportamiento de las AFOs y cómo ajustar la rigidez para mejorar la realización de las ABVDs.

*Palabras clave:* Actividades de la vida diaria, Órtesis de tobillo, Rigidez, Tobillo

**Abstract**

The capacity to perform basic activities of daily living (ADLs) is essential for personal independence. This requires multi-joint coordination and proper voluntary control, which is normally limited in people with neurological and motor disorders. Ankle-foot orthoses (AFOs) are often used to support ankle motion and improve mobility in these individuals. A key feature of these devices is the stiffness at what the AFO is configured, which highly influences the outcomes. This study focuses on analyzing the effects of different ankle stiffness conditions during ADLs. Five healthy subjects wore the inGAIT-VSO orthosis while performing ADLs at four different conditions (Low, Medium, High and No stiffness). The results show that increased stiffness reduces ankle range of motion (ROM) and influences muscle activity with differences across activities. These findings might provide valuable insight into AFOs behavior and stiffness adjustments to enhance performance in ADLs.

*Keywords:* Daily-life Activities, Ankle-Foot Orthosis, Stiffness, Ankle

## 1. Introduction

Basic Activities of Daily Living (ADLs) are defined by (Mlinac and Feng, 2016) as the essential abilities required to meet fundamental physical needs and maintain personal independence. These activities include walking, standing, climbing stairs, and maintaining balance, as well as tasks related to personal hygiene, dressing, toileting, and eating (Pashmdarfard and Azad, 2020). The performance of ADLs often involves motor actions such as bending, standing up, or squatting. Many of these tasks require complex coordination of lower limb joints.

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People with neurological disorders often present limitations to perform ADLs, which is closely associated with a reduced quality of life and increased dependency on others (Mlinac and Feng, 2016; Pashmdarfard and Azad, 2020). In those individuals with ambulatory capabilities, significant muscle dysfunction arises at distal joints of the lower limbs (Conner et al., 2022). As the ankle joint plays a key role in maintaining balance, enabling mobility transitions, and contributing to efficient gait mechanics (van Noort et al., 2024), impairments at the ankle can significantly limit the ability to perform these biomechanically demanding tasks.

Ankle-foot orthoses (AFOs) are commonly prescribed in conditions such as stroke (Sankaranarayan et al., 2016), cerebral palsy (CP) (Meyns et al., 2020; van Noort et al., 2024), and others (Lora-Millan et al., 2023) to assist and support mobility in these individuals. The stiffness of an AFO is a key parameter that defines the torque applied at the ankle joint per degree of joint rotation (Yoo et al., 2025). There is growing evidence that highlights the importance of matching this stiffness to the patient's specific motor impairments to optimize functional outcomes (Meyns et al., 2020; Yoo et al., 2025). While this matching is commonly studied in the context of overground and flat gait, its relevance may extend to other ADLs, which also require precise ankle control.

In this study, we evaluate the effects of ankle stiffness in the performance of different ADLs. We will use a variable stiffness AFO, the inGAIT-VSO (van Noort et al., 2024), to understand how it influences the performance of ADLs such as walking on inclined surfaces, cycling, standing from a chair, or lifting objects from the floor. Although the inGAIT-VSO is primarily intended for children with cerebral palsy (CP), the results may be relevant to anyone using an adaptive AFO. The outcomes of our study can provide valuable insights into the device's mechanical behavior and help to determine whether the effects of different stiffnesses keep consistent across ADLs, which might be useful for the broader applications of AFOs in real-life contexts.

## 2. Methods

### 2.1. Activities selection

We identified different ADL following a methodology similar to the one used in (Grimmer et al., 2020). These basic movements are not only essential on their own, but also sustain for more complex daily tasks, such as dressing, grooming, or transferring. Although in our selection most of the activities remained the same as in (Grimmer et al., 2020), we excluded some and modified others to better fit our specific lab conditions. The selected ADLs included (Table 1):

- Walking at controlled speeds: this activity was selected because it is fundamental and critical for physical displacement. We evaluated three different speeds, representing slow, normal and fast walking. Based on references from (Fukuchi et al., 2019) and (Murtagh et al., 2021) we selected 4.4 km/h as the normal speed. The slow and fast speeds were set by decreasing and increasing this value by 45%, respectively, resulting in 2.4 km/h and 6.4 km/h. These tasks simulated level-ground walking and were performed on a treadmill (CLIMB by DOMYOS, Decathlon) to precisely control speed. Each condition involved 2 minutes of continuous walking.

- Ramp ascent walking: not all terrains are flat, and navigating inclines is a common part of daily life, such as walking on ramps or hilly terrains. We selected a ramp up with 20% of inclination on the treadmill (CLIMB by DOMYOS, Decathlon). Participants walked for 2 minutes at the slow speed of 2.4 km/h to ensure controlled execution of the movement.

- Cycling: although commonly associated with sport and recreation, cycling also represents a repetitive and controlled lower-limb activity that may improve reciprocal inter limb coordination, enhancing stepping performance and gait quality (Damiano et al., 2017). In our experiment, cycling was performed at an ergometer (R5i Recumbent Bike, LifeSpan) at 60 rpm and 101 W for 2 minutes.

- Sit-to-stand: this transition is essential for mobility and independence. Starting from a seated position, at a 44 cm high chair without armrests, participants stood up, providing data on transitions between postures. This task was repeated 10 times.

- Lift objects from the ground: two lifting methods (stoop and squat) were performed, as this movement is critical for various ADL, such as picking up objects, and other routine tasks that require bending and lifting. The ability to perform these lifts efficiently is essential for maintaining independence and engaging in everyday activities. For this activity, the participant stood with their toes touching a board, on which a 4 kg weight was placed. Then, the weight was lifted according to the instructed lifting technique (stoop or squat) along 10 repetitions each.

Table 1: Selected experimental activities representing ADLs.

| Activity | Duration |
|---|---|
| Walk at 2.4 km/h | 2 minutes |
| Walk at 4.4 km/h | 2 minutes |
| Walk at 6.4 km/h | 2 minutes |
| Walk at 20° & 2.4 km/h | 2 minutes |
| Cycling at 101 W & 60 rpm | 2 minutes |
| Sit-to-stand | 10 repetitions |
| Stoop lifting 4 kg weight | 10 repetitions |
| Squat lifting 4 kg weight | 10 repetitions |

### 2.2. Variable stiffness orthosis

The inGAIT-VSO van Noort et al. (2024) was used for this experiment. It incorporates a passive mechanism that generates a non-linear ankle torque-angle relationship, active during both stance and swing phases of gait. The stiffness magnitude can be manually adjusted, allowing shifts in the torque–angle curve without the need to replace components (Figure 1). The sensors of the inGAIT-VSO enabled data acquisition without the use of complex laboratory equipment.

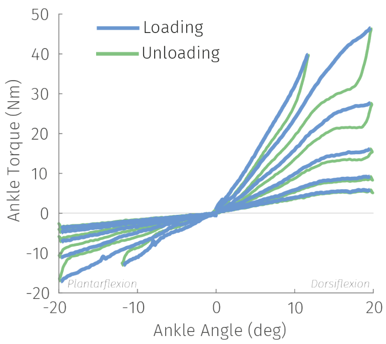


Figure 1: Torque-angle relationship curves of inGAIT-VSO.

### 2.3. Experimental protocol

Five healthy participants, three female and two male, average age 23 ± 2.19 years, average weight 55.90 ± 3.09 kg participated in this study. Each participant was informed about the study details and provided their informed consent.

Before data collection, participants received assistance in putting on the inGAIT-VSO device to ensure proper fit. They were then given time to walk around, familiarize themselves with the device, test the setup, and report any discomfort. After the familiarization period, the inGAIT-VSO was calibrated to ensure that zero angle (neutral position) occurred when the shank was perpendicular to the foot. Aditionally, muscle activity (EMG) of the gastrocnemious lateralis (GL) and tibialis anterior (TA) were assessed unilaterally on the dominant leg. Participants were asked to perform the maximum voluntary contraction for each measured muscle.

Each of the ADLs indicated under section 2.1 was performed for four different conditions: (1) wearing the inGAIT-VSO with Low stiffness (0.2 Nm/kg, as peak restoring torque at 12° of dorsiflexion (DF)), (2) Medium stiffness (0.4 Nm/kg at 12° of DF), (3) High stiffness (0.6 Nm/kg at 12° of DF), and (4) No stiffness. The same shoes were used in all conditions. The values for peak restoring ankle torque were determined in a previous study (van Noort et al., 2024) to align with the range reported in the literature. The 12° of DF approximately corresponds to the maximum DF observed during the stance phase of a healthy gait.

The order of the selected activities was kept constant, while the order of the stiffness conditions was semi-randomized for each participant, with half of them starting with the No stiffness condition and the other half finishing with it. The remaining stiffness conditions were assigned randomly to minimize potential bias due to order effects. Participants did not receive information about the condition they were in, except for the No stiffness condition, as it involved removing the leaf spring from the device.

At the end of the experiment, participants completed a brief questionnaire indicating the overall discomfort of the device and the perceived difficulty of each activity, comparing, for each stiffness condition, their performance while using the inGAIT-VSO with their performance on the same tasks when not using any device. Both aspects (discomfort and perceived difficulty) were rated on a Visual Analogue Scale (VAS), ranging from "very comfortable" (0) to "very uncomfortable" (10) and "much easier" (0) to "much harder" (10), respectively. Additionally, participants were asked which stiffness condition they preferred first, second and third (excluding the No stiffness condition).

### 2.4. Data acquisition

During the experiments, ankle angles were recorded using two magnetic encoders (AS5048b, AMS-OSRAM AG, Premstaetten, Austria) integrated in the inGAIT-VSO. Foot pressure was recorded using three force-sensitive resistors (FSRs) (FlexiForceA502, Tekscan Inc, MA, USA), placed on the insoles: at the heel of both feet and at the toe of the right foot. For the sit-to-stand and lifting tasks, an additional sensor was used to allow the experimenter to press it and indicate the start and end of each repetition. All signals were sampled at 100 Hz.

EMG was recorded using 2 bipolar electrodes (Trigno Delsys, Natick, MA, USA) with a sampling rate of 1926 Hz. These sensors were placed on the GL and TA of the participant's dominant leg.

Data from the inGAIT-VSO and EMG sensors were synchronized using a trigger signal. Once the inGAIT-VSO system was connected and initiated, it automatically triggered the EMG sensors to begin data collection. To finalize the recording, the same trigger from the inGAIT-VSO ensured stopping the EMG recording.

### 2.5. Data processing

Data were treated per ADL and stiffness condition and processed using MATLAB 2024b (MathWorks, Natick, MA, USA). EMG data were pre-processed to remove noise and artifacts. This involved band-pass filtering (30-300 Hz), full wave rectification, and low-pass filtering (3 Hz). The resulting linear envelopes were normalized to the maximum activation observed in the maximum voluntary contraction test.

After pre-processing, all data were resampled to the same frequency (100 Hz) and segmented based on the characteristics of each activity. For walking, inclined walking and cycling, segmentation was performed using gait or cycling cycles. The remaining activities were segmented based on the start and end of each repetition, which was manually indicated by the experimenter using an external sensor. Each cycle/repetition was linearly interpolated, resulting in 300 data points per cycle/repetition.

Averages of segmented data were computed for each participant, stiffness and ADL. Finally, data of the same stiffness condition and ADL were averaged across participants and used to calculate standard deviations (SD).

With the processed data we computed three key quantitative variables and analysed the subjective opinions given by the participants' in the questionnaires. The quantitative variables include (1) the ankle range of motion (ROM), (2) the effort exerted by each muscle computed as the integral of normalized EMG activity of each muscle along the cycle/repetition (cycles exceeding ± 1.5 standard deviations from the mean were excluded), and (3) the execution time for the sit-to-stand and lifting object activities.

### *2.6. Statistics*

Mean and SD were the main descriptive statistics used to present the results of ankle ROM, EMG integrals, duration of activity, general discomfort, and perceived difficulty across participants.

The effects of walking surface inclination and stiffness condition on ankle ROM were assessed using a two-way repeated measures ANOVA, with two within-subject factors: STIFFNESS CONDITION (No, Low, Medium, High) and INCLINATION (0°, 20°). The normality of residuals was evaluated with the Shapiro-Wilk test.

The effects of walking velocity on ankle ROM under different stiffness conditions could not be assessed with a two-way ANOVA test, as residuals violated the assumption of normality. However, since the Shapiro-Wilk test confirmed normality of the velocity within each stiffness condition – except for the Medium stiffness condition – one-way repeated measures ANOVA tests were applied.

The effects of stiffness conditions on ankle ROM were analyzed separately for each ADL. Walking normal, walking fast, walking ramp, sit-to-stand and lift squat activities met the normality assumption (verified using the Shapiro-Wilk test), and were analyzed using one-way repeated measures ANOVA. For the remaining, a non-parametric Friedman test was performed.

When interaction effects were found in any of the ANOVA tests, a Tukey-Kramer post-hoc test was performed. For Friedman tests, a Wilcoxon signed-rank test with Bonferroni correction was used. These post-hoc tests were used to identify pairwise differences between stiffness conditions, walking speeds, and incline levels. Statistical significance was set at $\alpha = 0.05$. All statistical analysis was done using Matlab 2024b.

## 3. Results

EMG data of GL from patient P01 were removed for walking ramp and lift stoop due to signal errors.

### *3.1. Quantitative analysis*

All the activities, except for the lift stoop, showed a clear reduction in the ankle ROM as stiffness increased (Figure 2). Table 2 shows the percentage of this reduction in ROM compared to the No stiffness condition (used as a reference). Reductions ranged from 5.8% to 61.9% compared to the reference, with most of the values in the High stiffness condition exceeding 50% of ROM reduction.

Statistical analysis reported that variations in walking speed or surface incline did not result in any ankle ROM significant differences. However, it did for the interaction between stiffness and inclination ($p = 0.0003$). When looking to the stiffness conditions, it was found that for all activities, except walking slow and lift stoop, the ankle ROM was significantly different between conditions ($p = 0.0009$ for walking normal, $p = 0.0006$ for walking fast, $p = 0.0001$ for walking ramp, $p = 0.0189$ for cycling, $p = 0.0040$ for sit-to-stand and $p = 0.0079$ for lift squat). Pairwise comparisons between specific stiffness conditions reported statistical differences between No and High stiffness conditions for walking normal ($p = 0.0319$), walking fast ($p = 0.0340$), walking ramp ($p = 0.0054$) and sit-to-stand ($p = 0.0406$); Low and Medium stiffness for walking ramp ($p = 0.0476$) and lift squat ($p = 0.0309$); and Low and High stiffness for walking normal ($p = 0.0162$) and walking fast ($p = 0.0425$). Cycling showed overall significant effects in the Friedman test, but pairwise comparisons did not show significant differences between specific pairs.

Looking to the average EMG across all muscles, all activities except walking ramp and cycling reduced muscle activation under the Low stiffness condition when compared to the No stiffness condition (black crossing lines in Figure 3), with a relevant decrease for all of them: walking slow (-10.40%), walking normal (-7.46%), walking fast (-18.81%), sit-to-stand (-16.97%), lift stoop (-15.11%) and lift squat (-24.32%). The Medium stiffness resulted in higher activation levels than the Low stiffness for walking ramp, cycling, sit-to-stand, lift stoop and lift squat but the increased with respect to No stiffness was only for walking ramp (10.83%), cycling (29.06%) and lift stoop (6.89%). However, level walking resulted in decreased muscle activation for the Medium stiffness across the three speeds, slow (-14.25%), normal (-9.28%) and fast (-21.23%). The High stiffness condition presented the highest muscle effort across all activities, with relevant increase compared to the No stiffness condition for walking slow (6.80%), walking normal (7.83%), walking ramp (35.80%), cycling (40.97%) and lift stoop (11.38%).

For sit-to-stand, lift stoop, and lift squat activities, the duration of each repetition was not affected by the stiffness condition, with average values of 0.98 ± 0.10 s for sit-to-stand, 1.99 ± 0.25 s for lift stoop, and 1.72 ± 0.23 s for lift squat.

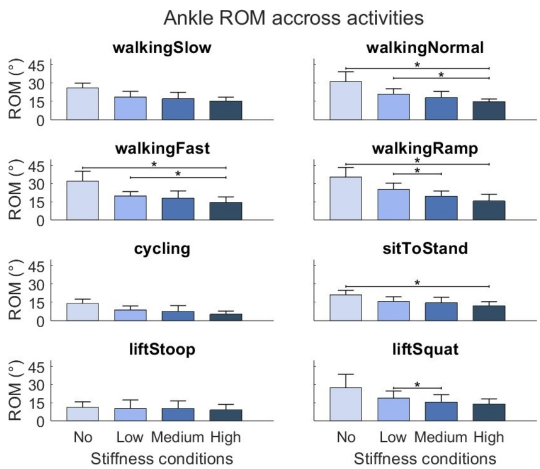


Figure 2: Mean and SD of ankle ROM across participants. Data are depicted for all activities and stiffness conditions. (*) represents significant difference between stiffness conditions.

Table 2: ROM reduction (%) compared to No stiffness condition

| Activity | Low | Medium | High |
|---|---|---|---|
| Walking slow | 29.0 % | 34.0 % | 41.0 % |
| Walking normal | 32.3 % | 41.6 % | 53.0 % |
| Walking fast | 38.3 % | 43.6 % | 54.9 % |
| Walking ramp | 28.7 % | 44.4 % | 55.8 % |
| Cycling | 37.4 % | 45.1 % | 61.9 % |
| Sit-to-stand | 25.9 % | 30.8 % | 41.7 % |
| Lift stoop | 7.7 % | 5.8 % | 18.4 % |
| Lift squat | 31.3 % | 43.1 % | 48.5 % |

### *3.2. Qualitative analysis*

Participants generally rated the activities as more difficult when using the AFO compared to performing the same activity without any device (Figure 4A), especially under the High stiffness condition, with a mean perceived difficulty score of 5.63 on a 0 – 10 VAS scale. The Medium stiffness condition had a mean score of 5.35, while for the Low stiffness condition it was 5.38.

The device was perceived as relatively comfortable, with an average discomfort score of 2.8 in a 0 – 10 scale (Figure 4B), suggesting minimal discomfort. All subjects preferred the lowest stiffness condition among the Low, Medium or High.

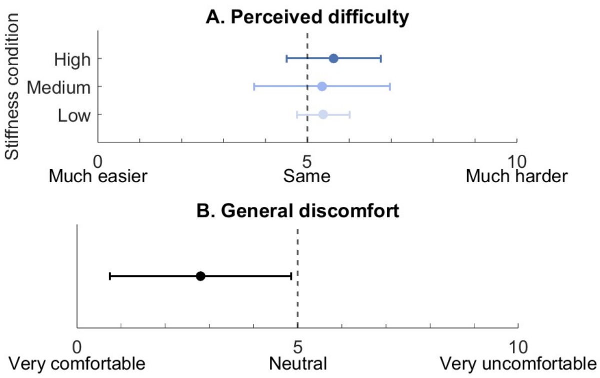


Figure 4: A. Mean and SD of perceived difficulty compared to performing the activity without any device, calculated from participants' ratings across all tasks. B. Mean and SD of perceived general discomfort with the AFO.

## 4. Discussion and conclusion

In this study, we evaluated how varying ankle stiffness condition influence ADLs using a variable stiffness AFO, the inGAIT-VSO (van Noort et al., 2024), in five healthy subjects. We proposed an experimental protocol in which activities were selected based on previous research that identified key ADLs (Grimmer et al., 2020). Overall, our findings indicate that stiffness does not affect all activities equally, and its impact is highly dependent on the demands of the task and the individual's adaptive strategies. These outcomes may be valuable for future research and the application of these type of AFOs for patients with different motor disabilities.

### *4.1. Quantitative analysis*

All analyzed activities showed reductions in ankle ROM with the introduction of any stiffness condition, generally increasing these reductions as stiffness increased. Despite the reductions in ROM across stiffness conditions, statistically significant differences were limited to the specific activities and conditions detailed in the Results section. This could be attributed to the high inter individual variability, even being healthy participants. Previous studies Sakanaka et al. (2021) have revealed that there are differences in intrinsic ankle stiffness between individuals, which may lead to different ankle movement strategies.

Regarding the muscle activity, except for walking ramp and cycling, lower EMG was found with the Low stiffness than with the No stiffness, which may be explained by the partial support the AFO can provide to the movement while still allowing considerable ankle freedom. Comparing to Low, the Medium condition probably introduced a mechanical restriction that participants compensated by increasing ankle muscle activity, trying to perform the same movement. However, level walking reduced muscle activity, suggesting greater support for these activities. With the High stiffness, the ankle movement restriction was so elevated that it required the highest ankle muscles activation to overcome it. That explains why the averaged EMG for the High stiffness was higher than with the No stiffness condition for the majority of the activities except for walking fast, in which the decrease was minimal. Results showed that the changes in muscle activity from Low and Medium stiffness conditions, compared to No stiffness, were similar for walking and cycling activities, while the High stiffness introduced a relevant increase in muscle effort. In contrast, sit-to-stand and object lifting activities showed the largest difference between Low and Medium stiffness conditions. This suggests that stiffness sensitivity is activity-dependent.

Although AFO stiffness had a clear impact on ROM and muscle activity, it did not significantly affect the duration of activities in which no speed was imposed. Task duration remained relatively constant across conditions, suggesting that stiffness mainly altered movement quality rather than task completion time.

### *4.2. Qualitative analysis*

Perceived task difficulty varied depending on the activity. Medium stiffness showed the greatest variability in perceived difficulty across activities. For example, incline walking and fast walking with medium stiffness were perceived as more difficult than performing the same tasks without the device. In contrast, the same stiffness level was perceived as easier than no device during non-displacement activities such as sit-to-stand and object lifting.

Overall, using the AFO was associated with increased perceived difficulty compared to not using it. For all stiffness conditions, the mean perceived difficulty exceeded the value of 5 –the baseline rating– for each stiffness condition (Figure 4A), indicating a general increase in task challenge when wearing the device.

Interestingly, although activities were perceived as least difficult under the Medium stiffness, participants perceived the

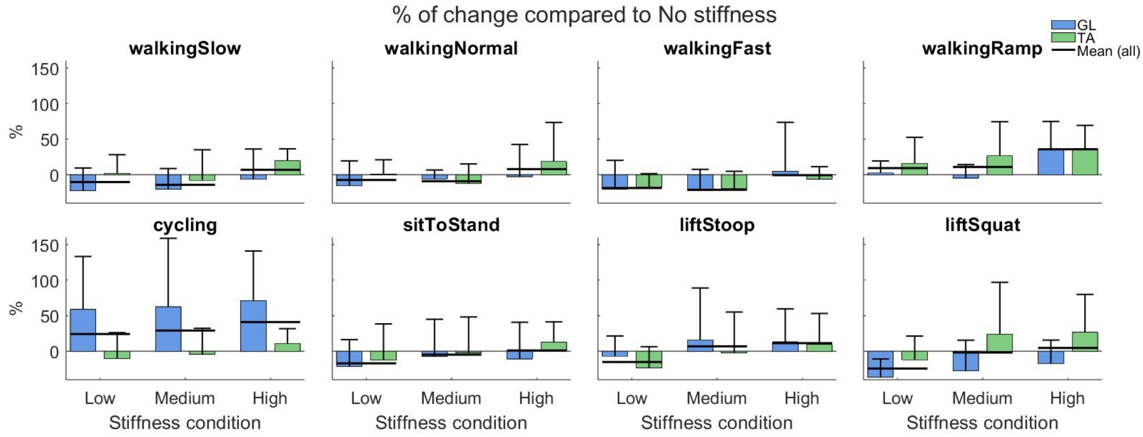


Figure 3: Relative muscle activations expressed as percentage of change compared to the No Stiffness condition. Bars show the mean and SD (% of change) across participants for each muscle. Horizontal black lines represent the average across all muscles for each condition. Positive values indicate an increase, and negative values a reduction, relative to the No Stiffness condition.

Low stiffness as the most comfortable. This apparent contradiction may be explained by the greater consistency in perceived difficulty across different tasks with the Low stiffness condition. For daily activities, participants may prioritize predictable performance over absolute ease for specific tasks.

Comfort ratings were generally positive. The mean discomfort score (Figure 4B) suggests that the inGAIT-VSO meets comfort standards for daily wear, as it was perceived to be relatively comfortable across conditions.

### *4.3. Study limitations and future considerations*

We acknowledge several limitations in this study. First, the small sample size (5 participants) might limit the generalizability of the results. Second, we miss some relevant ADLs, such as climbing stairs, which we could not assess due to lab constraints. Finally, EMG activity was only recorded from two muscles related to the ankle joint (GL and TA). Incorporating additional muscles could provide deeper insights into compensatory strategies with other joints that participants might use to respond to different ankle stiffness conditions.

Future studies should also consider the evaluation of these ADLs in participants with neurological disorders to define how the outcomes of this research translate to individuals with limitations.

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