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Influence of Motion Restrictions in an Ankle Exoskeleton on Gait Kinematics and Stability in Straight Walking

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Abstract— **Exoskeleton devices may impose kinematic constraints on a user's motion and affect their stability due to added mass and inertia, but also due to the simplified mechanical design. This study explores the impact of kinematic constraints imposed by exoskeletons on user gait, stability, and perceived discomfort. Specifically, it examines how the varying degrees of freedom (DoF) in an ankle exoskeleton influence these factors. The exoskeleton utilized in this study can be configured to allow one, two, or three DoF, thereby simulating different levels of mechanical complexity and kinematic compatibility.**

A pilot study was conducted with six participants walking on a straight path to evaluate these effects. The findings indicate that increasing DoF of the exoskeleton improves several criteria, including kinematics and stability. In particular, the transition from 1 DoF to 2 DoF yielded a larger improvement than the transition from 2 DoF to 3 DoF, although the 3 DoF configuration produced the best overall results. Higher DoF configurations also resulted in stability values that resemble more closely those of walking without the exoskeleton, despite the added weight. Subjective feedback from participants corroborated these results, indicating the lowest discomfort with the 3 DoF ankle exoskeleton.

I. Introduction

The ankle joint, with its three degrees of freedom (DoF), plays a crucial role in human locomotion by supporting loads up to four times the weight of the human body [1] and generating positive power during walking [2]. Exoskeleton devices that assist the ankle joint demonstrated significant reductions in metabolic energy expenditure [3] during straight walking, where ankle plantar-/dorsiflexion (PF/DF) movement is the most notable and the focus of 1 DoF assistance exoskeletons.

The design of an exoskeleton requires a careful balance between mechanical complexity, strength, and device weight. Limiting the number of exoskeleton DoF helps to reduce the mechanical complexity, inertia, and weight of these devices. A lighter exoskeleton design reduces the weight burden on the user, but it may also introduce limitations in terms of kinematics and stability. This reduced number of exoskeleton DoF can be beneficial for people with very unstable conditions, as it can improve their static stability [4]. However, for healthy individuals, designs that support all three rotations of the ankle are essential, since the ankle undergoes movement in all three DoF even during straight walking [5]. Allowing all three DoF enhances the ability to react to perturbations (ankle strategy) [6] and prevents the transfer of load to upper joints (hip and knee) for compensation [7]. Furthermore, ankle in-/eversion (IN/EV) and internal/external rotation (IR/ER) DoF are more prominent when turning and walking on curved paths [8], making exoskeletons designed only for straight walking less versatile for daily activities.

Kinematic compatibility, the ability to adapt to the posture of a human joint, depends on the adaptability and DoF of the exoskeleton frame and kinematics, as explored in our previous work [8]. The exoskeleton frame serves as the mechanical structure that holds the exoskeleton components in place and transmits the actuation torque to the cuffs. Designing ankle exoskeletons with 3 DoF involves trade-offs, leading to increased mechanical complexity and weight in rigid designs or decreased actuation forces in softsuit designs [8].

The number of DoF in an ankle exoskeleton affects the user's motion and stability. However, there is a paucity of studies that directly examine this effect. Most of the existing literature investigates the impact of gait restrictions using orthoses of varying stiffness. For example, [9] reported that ankle-foot orthosis (AFO) improves lateral stability, balance in static conditions, reduces postural sway, and increases walking speed in older adults. Similarly, [10] found that an increase in stiffness in an AFO reduces the maximum ankle PF/DF and the total range of motion (RoM), while significantly affecting knee kinematics, but not hip kinematics. Rossi et al. [11] observed significant differences between natural gait and walking with orthosis in children, attributed these effects to mechanical constraints induced by orthosis and not to added mass.

Some studies introduced the DoF restriction directly by locking the exoskeleton joints. For example, Olivier et al. [12] investigated the effects of ankle restriction on hip and knee kinematics at two different walking velocities, showing changes in knee and hip trajectory. When the ankle was locked, the hip RoM was larger and the knee RoM smaller. In addition, they observed that people adjust to the restrictions imposed with different strategies. Choi et al. [13] showed that a 2 DoF powered ankle-foot orthosis (PAFO) improved the user's stability significantly compared to a 1 DoF PAFO. McCain et al. [14] investigated the effect of restrictions on the ankle, knee and hip when using a 3D printed ankle stay and a knee brace to systematically limit the motion of these joints. Restrictions revealed a detrimental effect on the metabolic expenditure of walking, reducing the peak ankle power and knee RoM.

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According to Ranaweera et al. [15], restricting non-sagittal motions also affects muscle activation and causes significant changes in muscle activities.

The effects of restrictive frame or orthosis designs are closely linked to the impacts of added mass and inertia, necessitating their consideration in evaluations. The influence of weight and inertia on gait, energetics, and kinematics has been extensively studied. Heavy exoskeletons affect the RoM of the ankle and knee, decrease foot acceleration in the antero/posterior (AP) direction [16], and increase the swing times with increased inertia [17]. Metabolic demand is equally sensitive to similar relative increases in limb mass and moment of inertia [17]. Added inertia increases swing times and affects AP motion of the pelvis and the head-arm-trunk segment [16]. Browning et al. [18] reported longer strides and slower walking speeds with added weight, emphasizing the importance of weight placement. Jin et al. [19] also noted increases in step length and decreases in step height with added mass, while hip RoM increased and knee max flexion decreased. The negative influences of supplementary weight and inertia are intertwined with the negative effects of the kinematic restrictions. Therefore, a thorough analysis should take into account both aspects.

In this paper, we investigate the effects of the number of DoF in an ankle exoskeleton on the user's gait, ankle kinematics, balance and subjective perceived discomfort. Our study specifically aims to understand how different levels of mechanical complexity, represented by one, two, or three DoF in the ankle, affect these parameters. To achieve this, we designed an exoskeleton that could simulate one, two, or three DoF in the ankle, thus enabling creation of scenarios with varying mechanical complexity. We measured various gait parameters such as stride length, time, and height, as well as cuff rotation and RoM. Specifically, we analyzed the average values for PF/DF, IN/EV, and IR/ER, knee flexion/extension (FL/EX), hip FL/EX, their RoM, and similarity. Additionally, we also analyzed the stability of users and their subjective feedback.

By comparing the different exoskeleton configurations, we aim to identify the trade-offs between increased functionality (through additional DoF) and the potential drawbacks of added weight, inertia of higher mechanical complexity. Many ankle exoskeletons employ a simplified design with only 1 DoF [20], and the impact of this limitation is not well-explored in existing literature. Therefore, the findings of this study could provide valuable insights for the design and development of future exoskeletons, balancing the need for kinematic compatibility with the drawbacks of weight and inertia, potentially leading to improvements in user experience and performance.

The rest of the paper is organized as follows. Section II describes the exoskeleton, user study, data postprocessing and analysis methods. Section III reports and analyzes the results of the user study. Section IV discusses the implications, limitations, and future work of this paper. Section V concludes the paper.

II. Materials and Methods

This section introduces the design of the exoskeleton and the motion restriction method. It describes the conducted user study as well as the gait kinematic and stability metrics used to analyze the collected motion capture data.

A. Exoskeleton and DoF restriction

The ankle exoskeleton used in the study has been previously presented in [8]. It features a rigid frame design composed of a shank and foot section, shown in Fig. 1 (left). Both sections are joined through a parallelogram mechanism and multiple joints enabling all three rotations of the ankle, as shown in Fig. 1 (right). An additional foot frame DoF allows for forefoot rotation.

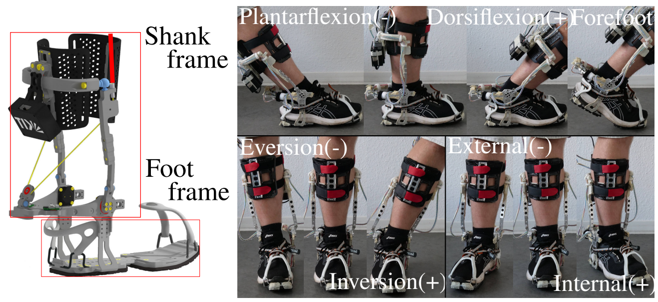

Fig. 1: Illustration of exoskeleton components and movements. (left) The shank and foot sections of the exoskeleton. (right) Demonstration of the exoskeleton's functionality, showcasing the three primary ankle joint rotations: plantar-/dorsiflexion (PF/DF), in-/eversion (IN/EV), and internal/external rotation (IR/ER), along with the forefoot rotation of the foot frame. (adapted from [8])

Figure 2 shows the relevant kinematic joints for the 3 DoF motion and size adjustment as well as the resulting three configurations of the exoskeleton. The foot frame is adjustable in several dimensions, as denoted by adjustable translation joints in Fig. 2. This includes adjustment of length and width to accommodate different sizes and types of shoes.

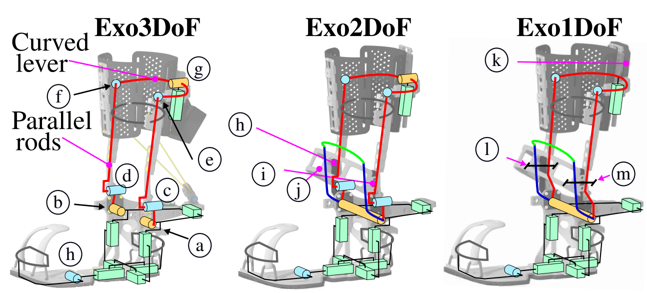

Fig. 2: Illustration of the three exoskeleton configurations: *Exo3DoF*, *Exo2DoF*, and *Exo1DoF*. The kinematic structure comprises various joint types: a hinge joint represented by "", a ball joint "", a hinge joint with angle measurement "", and an adjustable translation joint "". The explanations for each callout are provided in the text. (adapted from [8])

To restrict the human ankle DoF, different exoskeleton frame joints must be immobilized. By mounting fixture elements, i. e., blocking parts, on the existing exoskeleton structure, the ankle joint's DoF can be reduced from three to two or one, resulting in configurations *Exo3DoF*, *Exo2DoF*, and *Exo1DoF*. The following describes how the design restrictions were implemented.

The unrestricted 3 DoF kinematics, i. e., the *Exo3DoF* case is shown in Figure 2 (left). It features three hinge joints with integrated angle measurement marked with ⓐ, ⓑ and ⓖ, where ⓐ and ⓑ enable PF/DF. The IN/EV is enabled by hinge joints ⓒ, ⓓ and ⓖ, which are ortogonal to the parallel rods and the axis of hinge joints ⓐ and ⓑ. Additionally, the IR/ER is enabled by ball joints ⓔ and ⓕ.

In the *Exo2DoF* case, the exoskeleton mechanism restricts IR/ER by adding parts ⓘ, ⓙ and ⓗ. These constrain the rotation of hinge joints ⓐ and ⓑ. Consequently, the exoskeleton allows for PF/DF and IN/EV of the ankle.

In the *Exo1DoF* case, the IN/EV is restricted by screwing parts ⓘ and ⓙ to the parallel rods, as denoted by ⓛ and ⓜ. Furthermore, a fourth fixture part is added to constrain the hinge joint ⓖ. Consequently, only PF/DF motion is possible.

The restricted ankle DoFs of each *ExoXDoF* configuration are chosen to allow for the most commonly reported DoF combinations in ankle exoskeletons [20]. The unilateral ankle exoskeleton weighs 1.8 kg, wherein the foot frame section weighs 0.65 kg. The fixture elements together weigh 100 g. The exoskeleton is used passively; however, it has been designed to facilitate cable-driven actuation for plantar flexion motion in the future.

B. User Study

The user study assesses how the exoskeleton DoF constraints influence the kinematics, stability, gait parameters, and subjective perceived discomfort of individuals while wearing the exoskeleton and walking straight compared to not wearing the exoskeleton. The users also performed additional tasks, including: walking on a curved path, ascending and descending stairs, however, only the straight walking task is analysed in this paper.

Six healthy participants (four males and two females) took part in the study. Their information is summarized in Table I. All participants provided written informed consent before the study participation and all methods were performed in accordance with the Declaration of Helsinki. The experiment protocol was approved by the Karlsruhe Institute of Technology (KIT) Ethics Committee under ethical application for the JuBot project.

TABLE I: Participant Information

Height [cm]	Weight [kg]	EU shoe size	Age [y]
177.7 ± 9.3	77.7 ± 24.9	42.7 ± 2.5	24.5 ± 2.6

Values represent the mean and standard deviation.

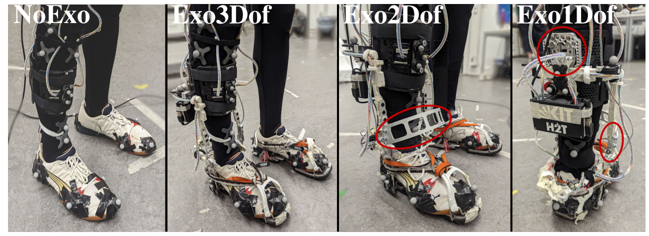

Fig. 3: A participant without and with the ankle exoskeleton in its three configurations. The parts added to fix certain DoF are marked in red.

For the straight-walking task, each participant walked at a self-selected speed along a 3 m straight path, turned around, walked back, and returned to the initial position. The walking path length was maximized while ensuring full motion capture functionality. Each participant's study session started with a random order of tasks for the *NoExo* condition to establish a baseline measurement without the exoskeleton. Each task was repeated four times. The three exoskeleton configurations followed, namely: *Exo1DoF*, *Exo2DoF*, and *Exo3DoF*, in a randomized order. As with the *NoExo* condition, the tasks were performed in a random order, with each task repeated four times. Each participant had a 3 min familiarization phase before the session and resting pauses between conditions and repetitions.

The *NoExo* case was performed without wearing of the exoskeleton and serves as a baseline. In the configurations *ExoXDoF*, the participants wore the exoskeleton on their right leg (1.8 kg), where the exoskeleton allowed the *X* number of DoF. The DoF restriction approach was already explained in Fig. 2. The users also wore a foot frame on their left leg (0.65 kg), to account for the thickness of the exoskeleton sole on the right leg, as shown in Fig. 3.

Before the study, the *Foot* frame was adjusted based on the participant's shoe size. During the donning process, the exoskeleton was aligned to ensure that the ankle axis coincided with the user's medial malleolus. The cuff was secured with velcro straps and tightened until a tight but comfortable fit was reached.

The motion of both the exoskeleton and the participant in the study was recorded by an optical Motion Capture (MOCAP) system (Vicon Motion System, Ltd, UK). Passive markers were attached to the exoskeleton and participant in a way that ensured a continuous tracking of the markers needed to calculate all three rotations of the ankle joint in all configurations. The marker configuration on the human body is shown in Fig. 3 and Fig. 4. In addition to the MOCAP data, exoskeleton sensor data was also collected. This included force myography (FMG) sensors measuring the mechanical action of muscle activation, which are further analyzed in [21].

C. Subjective Feedback

After each of the three exoskeleton sessions, participants were asked to complete a subjective discomfort questionnaire [22] adapted to the ankle exoskeleton. It consists of several

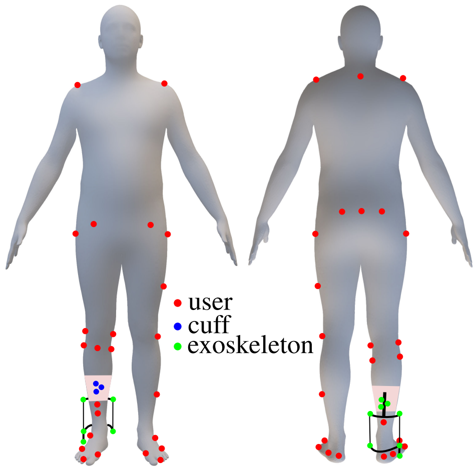

Fig. 4: Illustration of the MOCAP marker positions on the exoskeleton and the user. Red markers are attached on the user. Blue markers are attached on the exoskeleton cuff. Green markers are attached on the exoskeleton.

questions: whether the exoskeleton 1) is easy to use, 2) feels safe, 3) creates friction, 4) restricts movement, and 5) impairs gait on a 7-point Likert scale. Participants were also asked to rate their overall comfort using the same scale.

Note that the discomfort questionnaire covers the responses after the completion of all underlying tasks: walking straight, walking in a curve, and ascending/descending stairs. Gathering of responses is repeated after each condition/exoskeleton configuration. However, the quantitative analysis in this paper focuses solely on the walking straight task.

D. Stride Segmentation

All parameters and signals were evaluated on a stride basis, therefore all raw measurements were segmented into strides and averaged. The angles were segmented using the activation of the heel switch as seen in Fig. 5 (top left). All transient steps were removed to avoid starting and ending transitions. The selection criterion was the crossing of the zero absolute position of the X axis, as seen in Fig. 5 (bottom).

E. Gait Parameters

The analyzed gait parameters used to assess the effect the DoF reduction has on the participant gait include:

1) *Stride time* denotes the time between two heel strikes of the same foot.
2) *Right/left height* denotes the maximum height of the right/left foot during a stride.
3) *Right/left stride length* denoting the distance from one heel strike to the next heel strike of the same foot (shown in Fig. 5 (top right)).
4) *Stride width* denotes the maximum distance between both legs (shown in Fig. 5 (top right)).
5) *Walking speed* denotes the walking speed in m/s.

F. Kinematics

The effect on a user's kinematics is assessed by observing three ankle motions (PF/DF, IN/EV, and IR/ER) and the knee and hip FL/EX. For each angle, the averages and standard deviations of all strides from all participants were calculated for each exoskeleton configuration. The root-mean-squared error (RMSE) was used to compare the joint angle trajectories of *ExoXDoF* against the *NoExo* condition, i. e., the natural gait. A lower RMSE is preferred since it indicates a higher degree of similarity between the two conditions and therefore a more natural gait. The RoM denotes the maximum and minimum values of the trajectory average and the maximum and minimum standard deviation reached during the gait cycle.

Additionally, the rotation of the shank cuff around the shank axis, relative to the knee, is measured using markers placed on both the exoskeleton and the knee of the user. The rotation of the shank cuff indicates the angle between the cuff and the knee joint. An increased cuff rotation suggests more movement of the knee relative to the shank cuff, implying some IR/ER motion despite the exoskeleton's restriction, due to the compliance of the soft tissues around the shank. A lower cuff rotation is preferred as it indicates that the exoskeleton better follows the ankle rotations.

G. Stability

The participant stability is evaluated using a stabilogram of the trunk roll and pitch acceleration, as outlined in [13]. Maintaining balance of the upper body is important to avoid falling. Therefore, the stability is assessed based on the magnitudes of the detected accelerations of the upper body. To quantify them, a Gaussian ellipsoid is fitted onto the accelerations, and its two eigenvalue vectors are used to calculate a root-mean-square (RMS) value representing the instability. According to [13], a higher RMS value, i. e., the

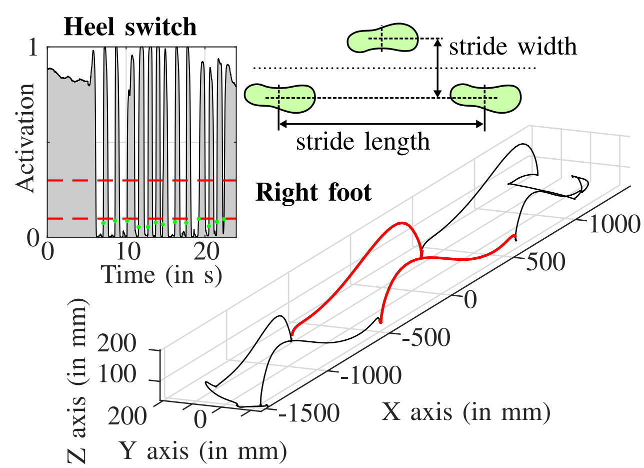

Fig. 5: Illustration of several relevant parameters relevant for this paper: (top left) heel switch activation example and detected strides in green, (top right) definition of the stride length and width, (bottom) an example of two segmented strides of the left leg.

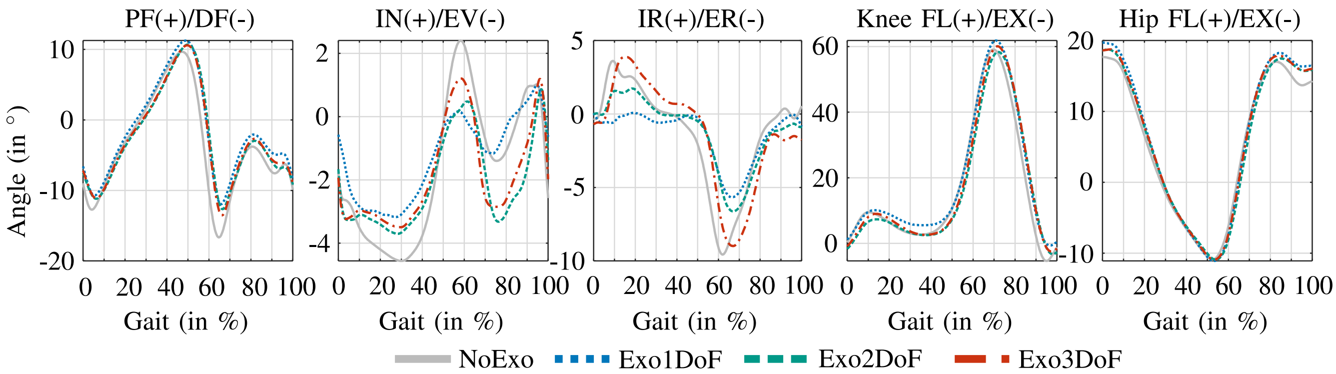

Fig. 6: Illustration of the user's kinematics: ankle plantar-/dorsiflexion (PF/DF), in-/eversion (IN/EV), internal/external rotation (IR/ER), knee flexion/extension (FL/EX) and hip flexion/extension (FL/EX). The plots depict the average of all strides for each configuration, highlighting the differences in kinematics between the four exoskeleton configurations. The motion direction is indicated in the title of the subfigures.

instability value, denotes greater swing of the trunk and indicates lower stability of the user. In the current study, trunk accelerations are calculated based on marker motion, positioned in the lower back and between the shoulder girdle. However, an inertial measurement unit (IMU) based system may also be used like demonstrated in [13].

III. Results and Analysis

A. Angle and RoM

This section presents the kinematics and RoM results. Figure 6 shows the averages and standard deviations of all strides and all configurations for ankle rotations (PF/DF, IN/EV, IR/ER), knee FL/EX and hip FL/EX. The averaged curves maintained a similar shape in all configurations compared to the *NoExo* condition. However, some discrepancies were observed. A slight phase delay was observed for PF/DF and IR/ER for all exoskeleton conditions compared to the *NoExo* condition. The phase delay is not visible in ankle IN/EV, knee FL/EX and hip FL/EX. Use of the exoskeleton increased the maximum plantarflexion (PF) of the ankle and reduced the minimum dorsiflexion (DF) of the ankle in all configurations. The changes between exoskeleton configurations are small.

The RoM of the IR/ER and IN/EV is only a few deg. It is evident that the exoskeleton does not completely restrict this motion, as some motion is still visible, likely due to the compliant nature of soft tissues. However, the most restrictive Exo1DoF features lower magnitudes than Exo2DoF or Exo3DoF.

The most prominent differences between the shape of all curves are evident in IR/ER. In this case, the *Exo1DoF* curve is flat in the first 0 % to 60 %, i. e., stance phase, of gait cycle. Changing the exoskeleton to the 2 DoF configuration results in an increase in the magnitudes of the angle, but only *Exo3DoF* returns its shape closer to the shape of the *NoExo* curve. A small phase delay can also be observed.

The knee FL/EX and hip FL/EX shapes appear to be the least affected. The knee has the largest RoM spanning from 0° to 60° and differs slightly between configurations at the heel strike and transition to the next stride. Similarly, there are some changes in the hip maximum flexion during the swing phase.

The similarity between curves, RMSE values, is depicted in Fig. 7. For PF/DF, IN/EV and hip FL/EX, *Exo3DoF* is the most similar to the *NoExo* case, as depicted by the smallest RMSE values, though the differences between configurations are small. For IR/ER, the values of *Exo3DoF* and *Exo2DoF* are similar and lower than *Exo1DoF* case. The knee shows the largest variations, as shown in large standard variation, where *Exo1DoF* shows the smallest RMSE value.

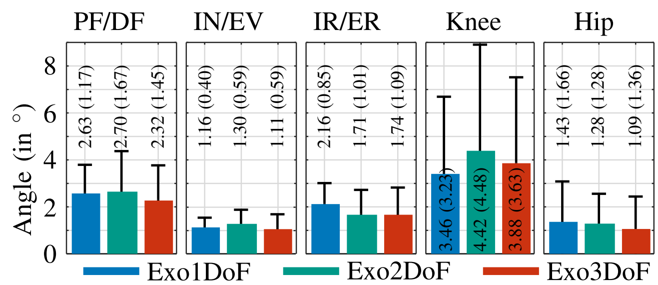

Fig. 7: Ankle rotation similarity of *ExoXDoF* to *NoExo* condition. The RMSE values are calculated between the averages of the respective configuration and the *NoExo* average for all strides of all participants. The standard deviation (vertical error lines) of RMSE values shows variability between the participants.

Finally, Fig. 8 shows the RoM of the curves shown in Fig. 6. The PF/DF RoM shifts with the introduction of the exoskeleton but appears to shift closer to the natural RoM with the increasing exoskeleton DoF. IN/EV RoM shows only a slight deviation with the increase of DoF. IR/ER RoM features the highest deviation of RoM with increasing exoskeleton DoF and returns nearly to the natural RoM of the *NoExo* case. Some changes in knee RoM can be observed when 1 DoF exoskeleton is worn, however, the RoM returns to the baseline with release of restrictions. The hip joint was least affected. A small change was observed for the *Exo1DoF* case, but no changes are observed for the increased DoF.

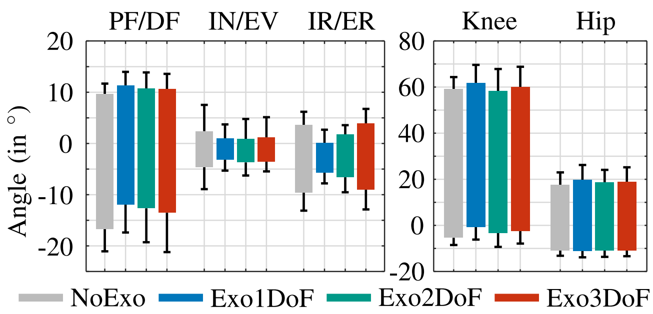

Fig. 8: RoM depiction for all three ankle rotations, knee and hip joint during straight walking for all configurations (*NoExo*, *Exo1DoF*, *Exo2DoF* and *Exo3DoF*). The blocks represent the maximum and the minimum angle of Fig. 6. The standard deviation (vertical error lines) values shows variability between the participants.

B. Gait parameters

This section presents the resulting gait parameters: stride time, foot height, stride length, width and walking speed. All parameters are collected in Fig. 9.

Wearing the exoskeleton increases stride time and decreases walking speed, with slight time deviation towards the *NoExo* condition as the number of DoF increases. The average and standard deviation of the height of the right foot remain nearly the same across all configurations. However, the average and standard deviation of the left foot height fluctuate between configurations. The right and left stride lengths for all *ExoXDoF* configurations, with no notable differences between both legs. The walking speed decreased and does not differ between *ExoXDoF* configurations. The stride width shows the largest differences and the largest standard deviation.

C. Cuff rotation

The relative cuff rotation displayed in Fig. 10 (left) offers a deeper look on the behaviour of IR/ER between different configurations. The cuff rotation is the largest for the *Exo1DoF* case. With increasing the number of DoF, the relative rotation of the cuff starts to decrease, indicating smaller rotations of the cuff relative to the knee. Condition *Exo3DoF* displays the smallest rotation.

Figure 10 (right) presents the RoM values. Changing from *Exo1DoF* to *Exo2DoF* shows a noticeable decrease in cuff RoM. However, changing from *Exo2DoF* to *Exo3DoF* does not show a noticeable improvement in cuff RoM.

D. Stability evaluation

Figure 11 displays stabilograms of the average roll and pitch accelerations of the trunk. Figure 11 (left) shows an example Gaussian ellipsoid fit (1σ and 2σ) for the Pitch/Roll accelerations for the *Exo3DoF* case with the corresponding eigenvectors. Figure 11 (middle) shows the ellipsoids (1σ) and the eigenvectors for all configurations. Figure 11 (right) shows the resulting instability based on the RMS of the corresponding eigenvectors shown for each configuration. Wearing of the exoskeleton (configurations *ExoXDoF*) results in a smaller ellipsoid (see Fig. 11 (middle)) and consequently lower instability values. The ellipsoid becomes larger, especially wider in roll axis, by releasing the DoF restriction from 1 DoF to either 2 DoF or 3 DoF. The change from 1 DoF to 2 DoF is greater than the one from 2 DoF to 3 DoF. Figure 11 (right) shows the highest variability (standard deviation) between participants for the *NoExo* case. However, wearing the exoskeleton (*ExoXDoF*) reduces the standard deviation, indicating that it introduces some restrictions that are similar between participants. Removing the exoskeleton DoF restrictions, i. e., moving to the configuration *Exo3DoF*, enhances instability values but does not restore them to the *NoExo* values.

E. Perceived discomfort

The results of the adapted comfort questionnaire are shown in Fig. 12. Descriptively, the overall comfort, ease of use, and feeling of safety, increase with the number of DoF. However, the difference between one and two DoF is greater than between two and three DoF. Furthermore, with more available DoF, the exoskeleton causes fewer movement restrictions and has a lower impact on perceived gait, as well as slightly reduces the creation of friction between the skin

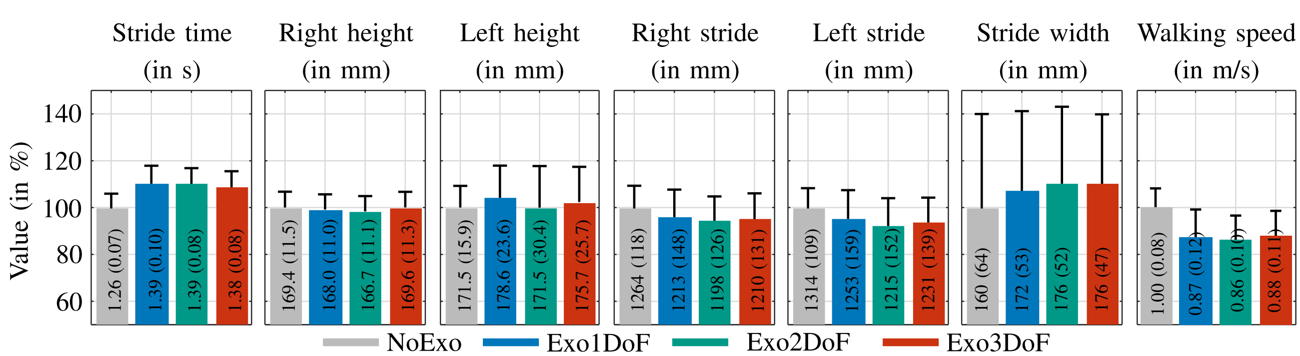

Fig. 9: Gait parameters normalized as percentage compared to the baseline for each condition. The gait parameters are the time of each stride (Stride time), average maximum foot height for either left or right leg (Right/Left height), length of the stride (Right/Left stride) and width of the stride (Stride width). The actual value and standard deviation are written in the respective column. The vertical error lines represent the standard deviation, indicating the variation between participants.

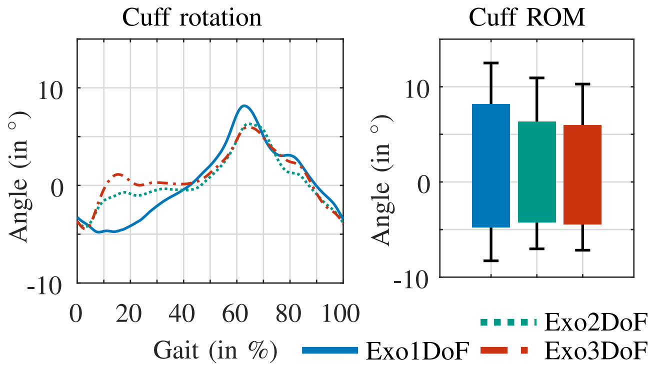

Fig. 10: Illustration of the cuff rotation and RoM. This is the rotation of the cuff relative to the knee on the axis of the shank. (left) The average cuff rotation for all strides of all participants shown for each condition, (right) the RoM depicted as a bar chart where the error ticks represent the standard deviation of all strides capturing the variability between participants.

and the exoskeleton. Nevertheless, the influence on gait (4.17 out of 7) and the restriction of movement (3.0 out of 7) are still quite high despite the release of the three DoF.

IV. Discussion

The study shows that wearing the exoskeleton results in a noticeable impact on the user's kinematics, gait parameters, stability, and subjective discomfort. Release of DoF restrictions improved the kinematic compatibility of the exoskeleton, demonstrated by RoM changes in ankle PF/DF and IR/ER. Thus, demonstrating improvement even for sagittal plane tasks, like walking. Furthermore, the RMSE values of PF/DF and IR/ER also get smaller with the release of restrictions, denoting greater similarity to the baseline. However, the ankle IN/EV does not show the same level of improvement. The hypothesis is that, compared to the other rotations, IN/EV features the smallest RoM in the straight walking task; therefore, the potential changes are not large.

According to the RMSE values, the knee was the most affected since it features the largest standard deviation; however, it also features the largest RoM. However, when examining RoM of the hip and knee, the changes were not as pronounced as in the literature [12].

The wearing of the exoskeleton impacted the gait parameters and removing restrictions led to slight enhancements in stride time and walking speed. Minimal changes in the height of the right leg were observed, which was equipped with the 1.8 kg exoskeleton. Interestingly, the left leg, wearing the 0.65 kg foot frame, exhibited larger standard deviation fluctuations compared to the right leg. Therefore, this discrepancy was further analyzed.

Each subject was re-evaluated independently to identify outliers, given the low number of participants. One participant showed a larger standard deviation, but removing this participant did not affect the overall analysis. The other participants had low standard deviations but different means, which, when combined, explained the larger standard deviation. It is hypothesized that users relied on their left leg to varying degrees to compensate for the heavier right leg. The literature also shows that people adjust to the restrictions imposed with different strategies [12], further supporting this observation. In the current study, only a unilateral exoskeleton setup was available, which possibly affected the study results. Future studies will employ a bilateral exoskeleton setup to prevent such asymmetries.

Stride width was the parameter that was the most affected and featured the largest standard deviation among the gait parameters. A likely explanation is that users increased their step width to avoid contact between the two foot frames, which also affected the height of the left foot. Thus, reducing the exoskeleton side clearance will be given a higher importance in the next design iterations.

In particular, the release of the DoF restrictions improved the instability values, bringing them closer to the baseline, thus improving the dynamic motion of users. However, the value did not fully return to baseline levels. Wearing the exoskeleton with full restrictions primarily blocks the IN/EV rotation, which affects medial/lateral (ML) (side-to-side) stability. It is not surprising that further unlocking the IR/ER does not result in the same level improvements, as it does not affect the ML plane. However, it is hypothesized that this is small since walking is limited to the sagittal plane and would increase for curved walking.

The instability values reported in [13] showed a different effect, with a decrease observed when transitioning from a 1 DoF to a 2 DoF configuration. In contrast, our study demonstrated the opposite behavior, with instability values increasing as more DoF were introduced, leading to reduced stability for the participant. Based on our findings, the exoskeleton device discussed in [13] imposes greater restrictions on users when wearing the 2 DoF exoskeleton in an unpowered state. While [13] does not provide stability values without the exoskeleton, further investigation is required to validate these findings.

The most interesting are the various subjective parameters regarding comfort and safety, shown in Figure 12. The plot shows that the overall comfort improves, with the unlocking of DoF. Here it has to be noted again that in the questionnaire, the participants answer after completing several tasks apart from straight walking, including curved walking, and walking stairs. Therefore, the user experience might have been influenced by that. The ("Ease of use") and ("Feels safe") categories also increased, showing that removing restrictions also influenced it, although technically the exoskeleton did not change. The users noted that the movements were restricted and that the exoskeleton affected gait. An increase in the DoF can therefore enhance the willingness to use the exoskeleton in the long term and highlight its advantages over other aids, such as rollators or crutches.

In general, for walking straight task, changing from 1 DoF to 2 DoF (unlocking IN/EV) revealed greater improvements than transitioning from 2 DoF to 3 DoF (further unlock-

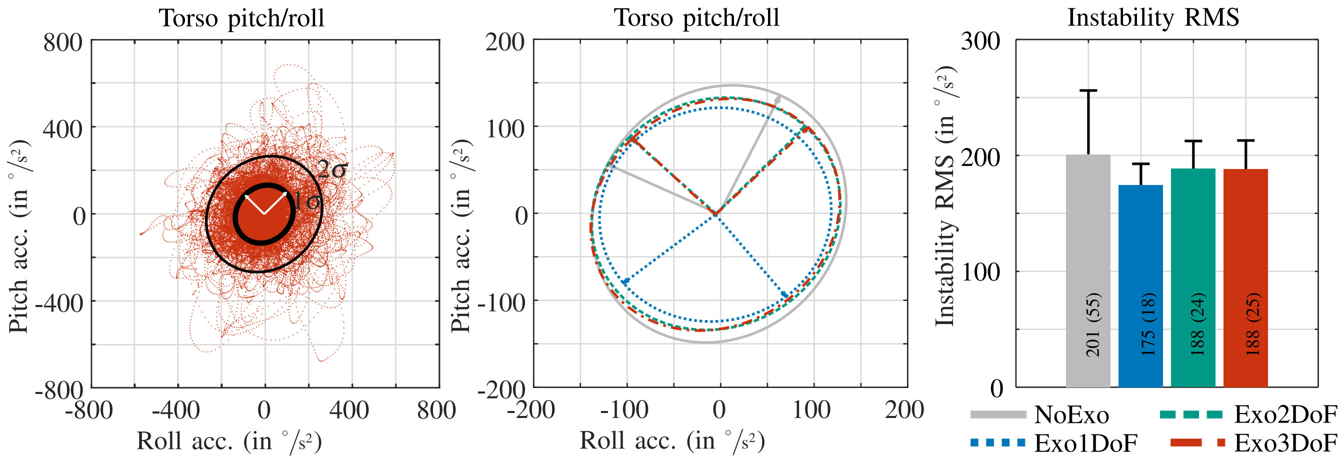

Fig. 11: Analysis of Torso Acceleration and Instability Across Configurations: (left) Example torso acceleration data for roll and pitch rotation, along with the corresponding Gaussian ellipsoid fit for the *Exo3DoF* configuration. (middle) Gaussian ellipsoids for all configurations. (right) Mean instability value for each configuration, averaged over all participants. Error bars represent the standard deviation of the averages for all participants and represent the variability between participants.

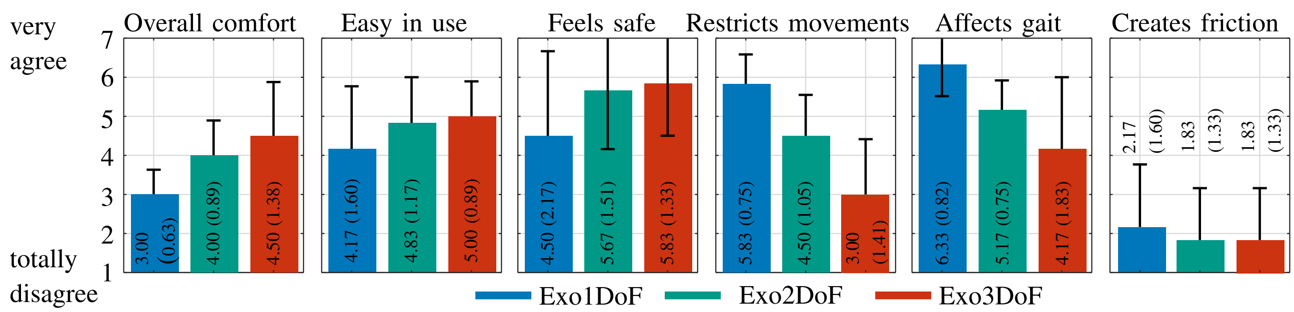

Fig. 12: Various subjective parameters regarding comfort and safety for each exoskeleton condition as a mean value. The questionnaire was answered immediately after each condition. Each question was introduced with: "The exoskeleton (is):". The answers must be given using a 7-point Likert scale from "totally disagree" (1) to "very agree" (7). The actual value and standard deviation are written on the respective column. The vertical error lines represent the standard deviation, indicating the variation between participants.

ing IR/ER). Thus indicating that unlocking IN/EV features greater improvements than additionally unlocking the IR/ER. This is shown through the RMSE values of IR/ER (Fig. 7), the rotation values of the cuff (Fig. 10) and the stability values (Fig. 11 (right)). The explanation is that restriction of the exoskeleton IR/ER has a limited influence on the ankle, since rotation is still possible due to the soft tissues around the shank. This is shown in Fig. 10 (right), as even under DoF restrictions the ankle can move, especially in IR/ER. The IR/ER is not as important IN/EV for walking straight tasks.

This work has limitations related to both the exoskeleton and study design and execution. The exoskeleton, weighing 1.8 kg, contributes to negative effects due to its increased weight and inertia. These adverse impacts on gait parameters, such as longer strides and slower walking speeds, align with findings in the literature [18]. Similarly, the observed increases in step length and decreases in step height with added mass are consistent with previous studies [19]. It is hypothesized that reducing the weight and optimizing the design of the exoskeleton could mitigate these negative effects.

A large issue of the proposed exoskeleton is the side clearance. Though the exoskeleton was built to be width adjustable and therefore result in the smallest side clearance, the clearance was still problematic. This is shown in the increased stride width while wearing the exoskeleton. The rigid sole is another hardware limitation that negatively affects the selected criteria. Previous studies have shown that rigid-soled shoes cause short phase delays in average curves [23]. We observed the same phenomenon in our study, as shown in Fig. 6.

According to these findings, the design goals for the next exoskeleton iteration will be:

- Further weight reduction and optimization.
- Removal of the rigid sole.
- Further reduced side clearance.

There were several shortcomings in the study design and execution. The small number of participants limited the ability to generalize the results. Furthermore, the short walk path in the experiment prevented users from achieving a stable gait. Finally, the familiarization phase was relatively brief and could have been more structured.

V. Conclusion

This paper addressed the impact of reductions in DoF on users and the role of ankle DoF in restoring ankle kinematics, gait parameters, and stability during straight walking. Additionally, information on participants' subjective discomfort was collected.

The findings of our study have important implications for the design of future lower body exoskeletons, which often neglect or simplify the ankle joint. A moderate increase in mechanical complexity by adding a second DoF provided benefits such as improved stability and reduced perceived discomfort. These benefits can be achieved by incorporating additional DoF, allowing for natural PF/DF and IN/EV if the task is limited to straight walking. However, the greatest improvement was observed when the ankle exoskeleton allowed for all three DoF.

For future work, we are developing a second iteration of the ankle exoskeleton to address current shortcomings, such as the rigid sole, side clearance, and weight optimization. These improvements will enable further investigations into the findings of this study.

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