Human-Centred Investigations toward Comprehending Human Adaptation Behaviour to Active Lower Limb Exoskeleton Use

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I. INTRODUCTION

Under the overarching goal of providing physical support to help rehabilitation patients regain mobility, numerous active lower limb exoskeleton designs have been developed and evaluated over the years. However, despite the laboratory experiments and clinical trials conducted to demonstrate the efficacy of various lower limb exoskeleton designs, the detailed comprehension of physical human-exoskeleton interaction (pHEI) remains unclear. In particular, the natural human adaptation behaviour during the exoskeleton familiarization process and what this adaptation process converges toward are not understood [1], [2].

Given humans' remarkable adaptive intelligence, the human body naturally adapts to changing conditions and varying parameters, and people often do so intuitively without even noticing it happening. In the context of lower limb exoskeleton use, the human body is subjected to external forces and moments exerted from the exoskeleton by means of motion support and, depending on the exoskeleton design, motion constraint. In addition, the user may want changes in the exoskeleton assistance parameters throughout the exoskeleton use, such as the timing, magnitude, duration, or any combination of such variables, and this cognitive agreement level is also reflected in the physical ergonomics. These exoskeleton-imparted and interactive loads are the variables which the users need to adapt over time as part of the natural neuromotor adaptation process. While individuals intuitively adopt unique adaptation strategies throughout the exoskeleton-assisted locomotion [3], how this process unfolds, as well as the inherent objectives, remain unclear.

In this work, we conduct human-centric investigations aimed at unveiling the human adaptation process in the context of exoskeleton-assisted locomotion. This human-centred investigation is toward providing initial evidence in understanding how exactly the human-exoskeleton adaptation process unfolds, deriving the human intentions from human movement and gait analysis, which are the necessary first steps for designing exoskeletons personalised to individual intentions, actions, and preferences. As a starting point, the changes and the course of the changes in lower limb kinematics and metabolic cost responses are closely studied. Rather than the usual statistics reporting of end-states or the averaged joint trajectories [4], changes in lower limb kinematics are analysed throughout the exoskeleton use. While this information is often overlooked or neglected, it holds valuable insights as to how the participants adapt during pHEI, as well as to identify the individual differences in the adopted strategies. In addition, a quantitative method for defining the steady state metabolic cost is explored in the absence of a clear, reasonable definition in the literature [5].

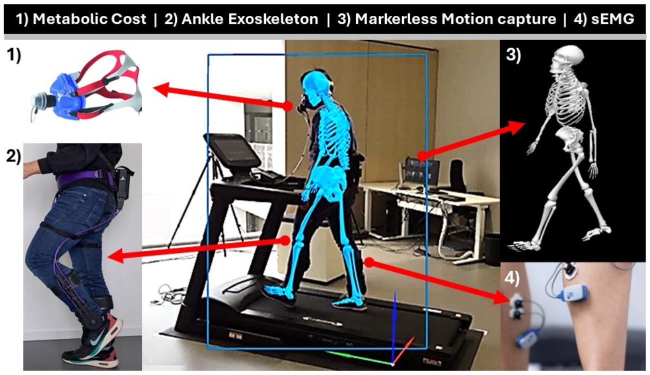

Fig. 1. An overview of the laboratory equipment used in this human-centred investigation of human adaptation to exoskeleton use.

II. METHODOLOGY

Only healthy young adults with no history of musculoskeletal injuries or mobility impairments are recruited in this study. A total of 9 healthy young adults participated in this study so far (6 female, 3 male, Age: $\bar{x}$ = 24.6 s = 3.6, Height in cm: $\bar{x}$ = 171.8 s = 10.0, Weight in kg: $\bar{x}$ = 68.7 s = 13.2). This study has been reviewed and approved by the KIT Ethics Committee (A2024-007). Considering that every individual walks differently and may adopt unique adaptation strategies, changes in joint kinematics are analysed individually per participant rather than focusing on statistical inferences. As opposed to the end-state to end-state comparison most commonly reported in exoskeleton evaluation studies, the course of the changes in biomechanical variables is studied individually per participant throughout the entirety of the experiment to capture the transient processes in adaptation behaviour. In addition, various qualitative and quantitative metrics are currently being developed and evaluated in this study.

A. Equipment

An overview of the equipment used in this study is shown in Fig. 1. The cable-driven active ankle soft exoskeleton

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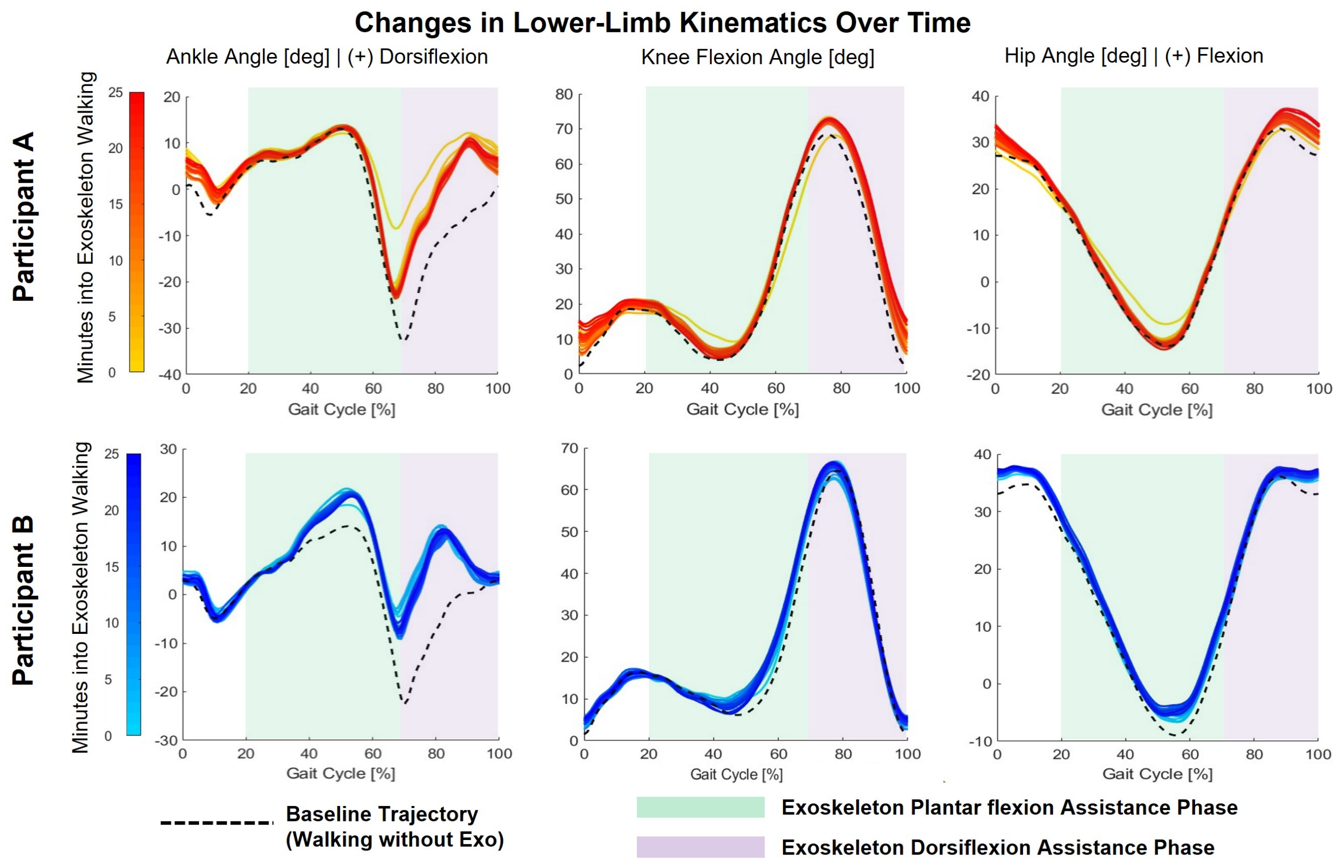

Fig. 2. An overview of sample key results in joint kinematics for 2 out of 9 participants. The lower-limb joint kinematic trajectories during the 25-minute exoskeleton-assisted locomotion normalized to the gait cycle, with the baseline reference shown with dashed lines.

(Spark, Biomotum) provides bidirectional assistance in both plantar flexion and dorsiflexion with predefined torque assistance profiles during gait [6]. While the long-term goal of this initiative is to establish a robust and generalizable methodology, the initiation of the investigation is done with a single-jointed ankle exoskeleton. This helps to reduce the complexity and variability as compared to starting with a full lower limb exoskeleton, which enables the study to emphasize the human-centred investigation of interest.

The markerless motion capture system (Theia3D, Theia Markerless) takes video footage of participants during the experiment, outputting the joint kinematics data upon post-processing. Despite the presence of the exoskeleton, the kinematic model of the user is seamlessly generated without occlusion. The portable indirect calorimetry system (K5, Cosmed) monitors the metabolic energy cost throughout the experiment. A total of 16 Surface Electromyography (sEMG) channels are employed (DTS Research, Noraxon) to monitor the changes in lower limb muscle activation levels. Specifically, electrodes are placed on the tibialis anterior, soleus, gastrocnemius medial and lateral, rectus femoris, vastus lateralis, biceps femoris, and gluteus maximus for both the left and the right.

B. *Experiment Protocol*

Before proceeding to the walking tasks, the preferred walking speed for every individual is determined. As opposed to fixed walking speed, usually set at relatively high walking speeds often without reasonable justifications [7], this method takes the subjective preferences and perception of walking efforts into the account. Specifically, the participants are asked to walk 10 meters at their own pace after being given the prompt: *Imagine you are going for a nice walk. For example, pretend you are walking by the Rhein river for about 30 minutes with amazing weather*. A 1-meter distance buffer on each end of the 10-meter markers ensured the participants had sufficient time to accelerate to their natural walking speeds.

The resting metabolic rate (RMR) is first collected during 4 minutes of sitting to establish the reference Metabolic Equivalent of Task (MET) [8]. The participants are then asked to walk on the treadmill at the predetermined speed for 6 minutes without the exoskeleton, in which the kinematic and metabolic baseline references for nominal walking without an exoskeleton are collected. After a 5-minute break, participants walked on the treadmill at the same predetermined speed, with the exoskeleton assistance for 25 minutes. The duration of 25 minutes is adopted based on the required time for exoskeleton adaptation, as reported in the literature using the metabolic cost stabilization definition [4], [9]. Lastly, the participants also performed exoskeleton walking with zero torque condition for 6 minutes, in which the exoskeleton actively tried to maintain zero motor torque to prevent providing any assistance or resistance against walking. This is to isolate the implications caused by the kinematic misalignment and joint limits imposed by the exoskeleton.

III. PRELIMINARY RESULTS AND DISCUSSION

Examples of the identified unique qualitative adaptation strategies are as shown in Fig. 2. In the case of Participant A, the participant adapted to the exoskeleton-assisted locomotion via compensating with higher hip flexion during the swing phase. In combination with the ankle trajectory converging to provide increased plantar flexion during push-off, the end effect of this adaptation mode is the ankle kinematics resembling closer to the baseline reference of normal walking without exoskeleton. The overall decreased plantar flexion angle is hypothesized to be attributed to the joint limit imposed by the exoskeleton, in which further analyses of the 6-minute zero-torque walking may provide additional insights.

In the other adaptation strategy shown by Participant B, the adopted strategy was to compensate via the ankle movements. With an increased overall ankle dorsiflexion during footflat and midstance, the participant kept the changes in hip and knee trajectories minimal throughout the 25 minutes. These intriguing adaptation modes are identifiable only via observing the course of the changes in kinematics, which would have been overlooked in statistical inferences typically done in the literature.

The adaptation process in the exoskeleton-assisted locomotion is often described using only the metabolic cost stabilization or sometimes simply with the assumption of metabolic cost stabilization [4], [5]. However, not only is the transient component of metabolic cost neglected with this approach, but there also exists no quantitative definition of the steady state. Examples of metabolic cost responses are as shown in Fig. 3. The dashed lines in the metabolic responses represent the steady state convergence margin of 0.12 W/kg. In the absence of a clear definition in the literature, this metric is adopted as the quantitative measure of metabolic cost convergence. While the 0.12 W/kg represents a significant 10% of 1 MET [8], additional scientific investigations involving frequency or phase domain analyses should be included to avoid contributing to the vagueness of the definition [10].

According to this new definition of metabolic cost steady state convergence, the metabolic cost response did not show convergence in the case of participant A, whereas the convergence had occurred for participant B after the 11^{th} minute into exoskeleton-assisted locomotion. Given that only 4 participants had achieved metabolic cost stabilization based on the provided definition, care must be taken when defining human adaptation behaviour using only the metabolic cost response. Relying only on metabolic cost may lead to an erroneous and indeterminate definition of human adaptation, as the metabolic cost is not guaranteed to reach steady state. In the case of Particiant A, the metabolic cost appeared to have temporarily achieved metabolic convergence and started deviating around 18 minutes into the experiment. This could have been attributed to fatigue from prolonged exoskeleton use. An analysis of sEMG data is currently underway to investigate this hypothesis further.

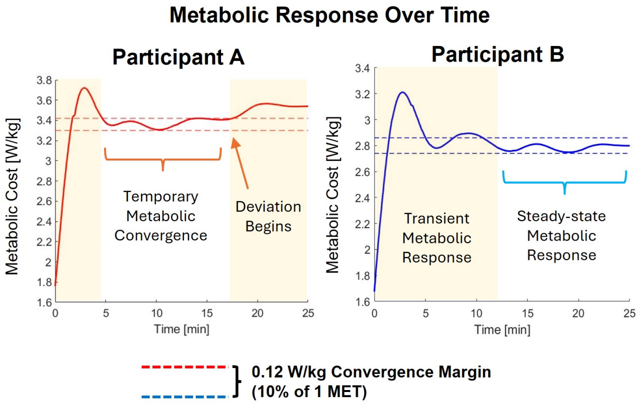

Fig. 3. The metabolic cost responses throughout the experiment in temporal domain in which the different responses are demonstrated by two sample participants.

IV. CONCLUSION AND FUTURE WORKS

Individual changes in kinematics provide valuable information on how this process unfolds differently for everyone, emphasizing the need for individualized analysis in understanding adaptation to exoskeleton-assisted locomotion. Unique kinematic strategies and non-uniform metabolic responses highlight the limitations of relying solely on steady-state metabolic cost to define human adaptation behaviour. Future works will include collecting additional data with larger participant samples, and investigating further into collection and analysis methods generalizable across other exoskeleton platforms. A key direction in this study involves identifying predictive factors that may inform personalized adaptation strategies. These efforts are aimed to support the development of adaptive, user-centric exoskeletons that better align with human intent and behaviour.

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