COB-2023-1784 Assessing the Joint Misalignment Effects in Rehabilitation Robotics: A Case Study

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Abstract. *Context: Designing safe control strategies for robotic rehabilitation requires addressing challenges such as modeling human behavior, ensuring safety operation, robustness and adaptability. A common assumption in these control strategies is that robot and human limbs share the same movement and joint rotation during assistance, enabling a unified and simplified model for system modeling. However, human joint kinematics are relatively complex to emulate precisely by robotic devices; this is due to body segment variability, ligaments and tendons stretching, and inherent migration of joint centers. Therefore, understanding the physical human-robot interaction (HRI) turns out critical when dealing with undesired forces produced by misalignment between the robot and the wearer's body, which must be minimal to prevent injury, discomfort and transmission looses of the robot-assisted joint torques. GAP: Even though proper force transducers can be positioned at the user-robot interface, quantifying joint misalignment remains difficult. An essential consideration for sensors in HRI systems is that high joint misalignment during motion might shift the contact area where the interaction force is measured, producing variability and unpatterned behavior. Consequently, an HRI force sensor must be validated with joint misalignment information to provide reliable measurements. Purpose: The objective of this work is to identify the misalignment of a human-robot interaction system for robotic rehabilitation purposes and study the effects of misalignment and interaction forces in different possible misalignment scenarios. Experiments were conducted using a robotic knee exoskeleton for walking trials with various misalignment configurations. Custom 3D-printed embedded HRI sensors, based on Force Sensing Resistors (FSR), were developed and placed at different contact points at the interface of the human leg and the knee exoskeleton to quantify HRI forces and identify misalignment levels. Results and Conclusions: The results showed a strong relation between misalignment level and walking speed during the physical HRI. It was observed that the duration of phases in the gait cycle was significantly affected by misalignment. These outcomes have implications for the design of modeling-based controllers. Inaccuracies in system modeling could result from a misunderstanding of misalignment, potentially impacting the performance of such controllers. By identifying and studying the effects of misalignment in HRI systems for rehabilitation purposes, safety, effectiveness, and user comfort can be enhanced, ultimately improving the rehabilitation experience and controller performance.*

Keywords: Rehabilitation Robotics, Human-robot interaction (HRI), Joint misalignment

1. INTRODUCTION

Robotic exoskeletons are increasingly utilized in physical rehabilitation settings, offering tremendous potential for improving mobility, enhancing physical strength, and accelerating recovery time (Hobbs and Artemiadis, 2020). However, one of the critical challenges in this domain lies in designing safe and effective control strategies that accurately interact with human kinematics and dynamics, taking into account variations across individuals and conditions (Escalante *et al.*, 2021; Dos Santos *et al.*, 2022). A significant challenge in designing rehabilitation robots is achieving optimal alignment between the robot and the human body, given the inherent complexities and individual differences in human joint kinematics (Leal-Junior *et al.*, 2018; Bartenbach *et al.*, 2015). In the context of exoskeleton design, alignment typically refers to the congruence between the rotation axes of the robot's and user's joints. Misalignment can occur when these axes do not perfectly coincide, leading to discomfort, increased risk of injury, and reduced effectiveness of the therapy (Zanotto *et al.*, 2015). Despite its critical importance, quantifying and compensating for joint misalignment in real-time during physical human-robot interaction (HRI) remains a significant challenge.

Previous studies have developed different solutions for assessing and compensating for joint misalignment in rehabilitation robotics. In Leal-Junior *et al.* (2018), Polymer Optical Fiber (POF) sensors were employed to detect and quantify HRI forces generated by lateral misalignment. The POF sensors were integrated into the robotic exoskeleton and proved sensitive to misalignment. In Bartenbach *et al.* (2015), a comprehensive study of joint misalignment effects on HRI in a

lower-limb exoskeleton was conducted. A passive exoskeleton equipped with an extensive array of sensors for detailed movement and force measurements was employed. However, this design required a complex misalignment compensation mechanism that increased the device's mechanical impedance. Although this work was aimed to cover the diversity of misalignment sources, its findings showed that effective misalignment compensation may require more complex, potentially bulky, and expensive solutions than simpler designs that assume ideal alignment. The work presented in Zanotto *et al.* (2015) emphasized the significant effect of knee joint misalignment on the user's gait and interaction forces between the user and the exoskeleton. The authors introduced controlled knee misalignment by adjusting the mismatch between the robotic thigh and human thigh lengths. Despite providing valuable insights, the approach did not consider other misalignment configurations, such as differences in link/limb orientation angles and rotational axes' centers. The definition of misalignment is still ambiguous, with a lack of generalization across different exoskeleton configurations.

This study aims to contribute to the ongoing discussion on misalignment in HRI systems for rehabilitation by introducing a novel approach for assessing and quantifying misalignment and HRI forces. We propose using Force Sensing Resistors (FSR) positioned at different contact points on the human leg and the knee exoskeleton interface. This work hypothesizes that measuring the interaction force in different contact points of the leg interface will provide valuable information about misalignment levels and interaction forces. We aim to investigate the influence of joint misalignment and the effects of speed-walking rehabilitation scenarios. For this, we aim to compare joint angle ratios and angle orientation of the limb and robot link for different configurations. This research focuses on enhancing the understanding of joint misalignment in the context of rehabilitation robotics, aiming to improve safety, effectiveness, and user comfort.

2. Experimental Setup

The EICoSI knee exoskeleton (Rifaï *et al.*, 2017) utilized in the experiments is depicted in Fig. 1. The knee joint rotation angle is determined by the incremental encoder installed in the exoskeleton. The device comprises two segments that can be attached to the wearer's thigh and shank region using straps and is worn on the user's right leg.
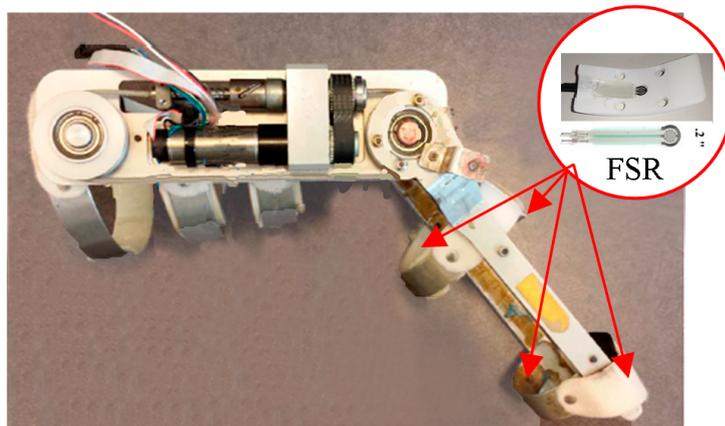

Figure 1. The EICoSI knee exoskeleton (Rifaï *et al.*, 2017)

The experimental setup incorporates an Inertial Measurement Unit (IMU) Wireless System from Xsens, as shown in Fig. 2a. Four IMUs were positioned, one on each limb and on the exoskeleton's link segments, to compute the human knee angle and capture the orientation angles of the shank and thigh segments of both the human and the robot (see 2b). Force-sensing resistor (FSR) sensors from Tekscan (Standard Model ESS102) were strategically placed at the interfaces between the leg and the robot cuffs. The FSR sensor has a force range of 0-4N, a length of 38.1 mm, and a sensing diameter of 3.81 mm, enabling precise detection of contact point forces at the interface. This study proposes using the FSR array (2a) to assess misalignment. Each FSR is embedded in 3D-printed cuffs. The sensor positions were arranged to measure interaction forces at four distinct points on the shank—front, back, and two different distal/proximal points relative to the joint.

Four experiments were conducted to examine the interplay between walking speed and misalignment. The position of the robot knee joint was varied in two ways: firstly, the device was sufficiently tightened to the knee to minimize shear forces and slippage; secondly, the device was shifted 10 cm downwards from the knee's normal position to introduce a misalignment between the human and the robot. An FSR-based insole was employed to detect the two main phases during gait: stance and swing. Details of these experiments are provided in Table I.
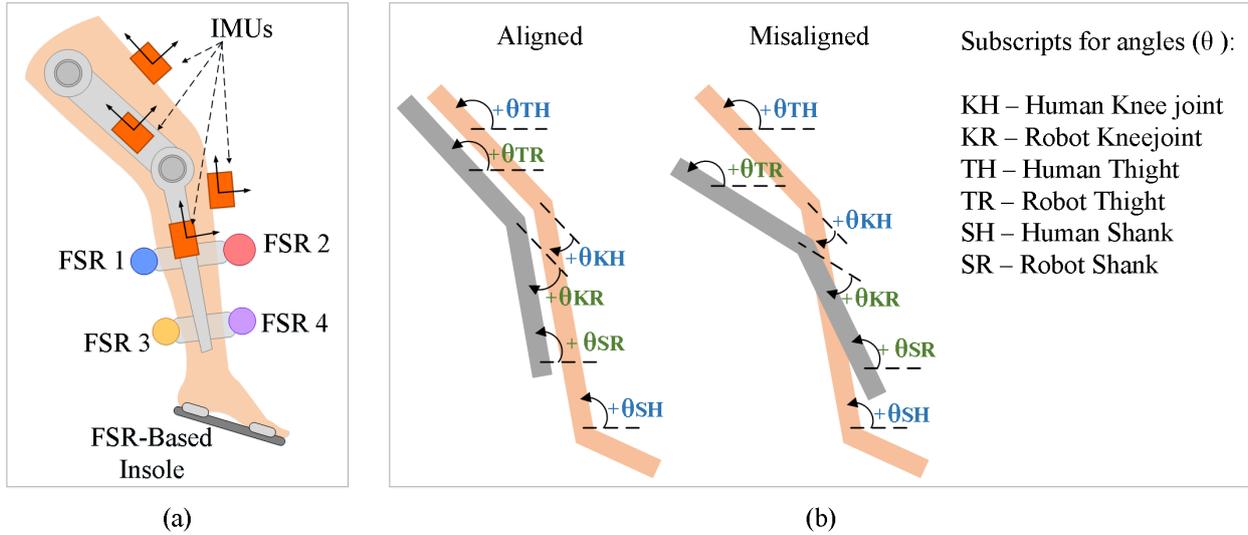
Figure 2. Experimental Setup and sensor positioning

Exp. Number	Robot Position	Walking Speed (m/s)
1	Aligned	1
2	Aligned	2
3	Misaligned	1
4	Misaligned	2

Table 1. Configurations of experiments

3. Results

Figure 3 presents the FSR signals for the experiments conducted in both aligned and misaligned configurations. All the signals were segmented across the gait cycle. Each voltage response of FSR sensors represents contact forces. These signals were normalized, bypassing any analysis of their magnitudes or RSM values. In these plots, the continuous signals represent the normalized mean values, while the triangle symbols represent the characteristic peaks of each signal. Table 2 shows the occurrence of Peaks in the FSR signals during the normalized time. The table was calculated to observe timing differences between the different types of experiments. In the table, gray cells indicate which experiment between aligned or misaligned performed earlier occurrence.

	Walking speed 1 m/s		Walking speed 2 m/s	
	Exp. 1 (aligned)	Exp. 3 (misallig.)	Exp. 2 (aligned)	Exp. 4 (misallig.)
FSR 1	0.3788	0.4766	0.2205	0.3154
FSR 2	0.6082	0.9091	0.3849	0.5822
FSR 3	0.4827	0.5234	0.2901	0.4313
FSR 4	0.6450	0.9780	0.4004	0.6253

Table 2. Normalized time occurrence of FSR peaks.

The mean ratios and differences of the knee joint (θ_K), thigh (θ_T), and shank (θ_S) angles between the human and the robot are computed and displayed as a bar plot in Figure 4. Here, the angle differences are denoted by a delta symbol (Δ) and the ratio by R. The mean angle differences are expressed in radians, while the ratio is dimensionless. Figure 5 presents the average cycle duration in percentages for the gait phases across all experiments. The stance phase for experiments with aligned and misaligned configurations is represented by blue and light blue colors, respectively. Similarly, the swing phase for experiments with aligned and misaligned configurations is denoted by red and salmon colors, respectively. Experiments with trajectory assistance are distinguished by a hatched fill pattern.
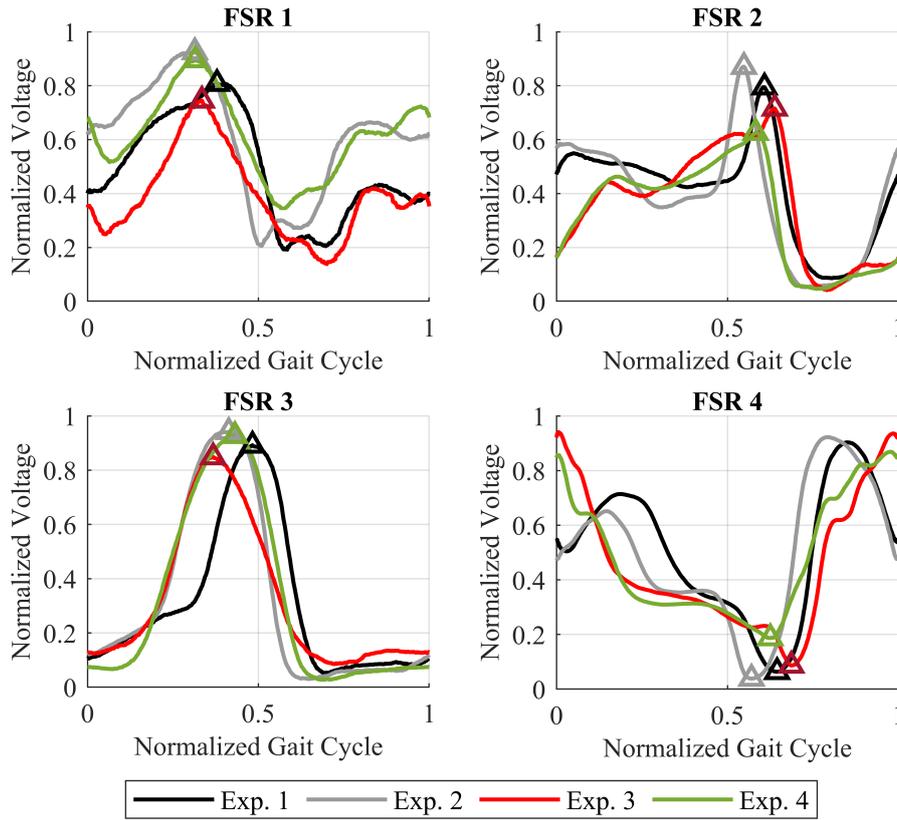
Figure 3. Normalized FSR signals segmented over the gait cycle..
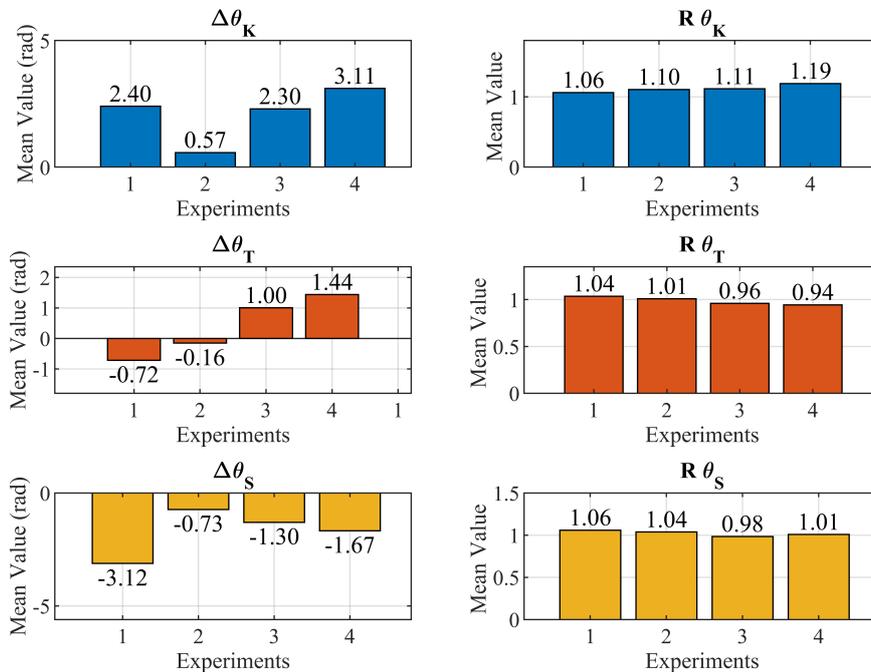

Figure 4. Bar plot of the mean angle ratios and differences (Δ for difference and R for ratio) between the human and robot for knee joint (θ_K), thigh (θ_T), and shank (θ_S) angles.

4. Discussion

All experiments show periodic FSR signals reflecting the gait cycle's fundamental biomechanics. However, differences emerge when comparing the aligned and misaligned configurations. As shown in table 2, aligned configurations
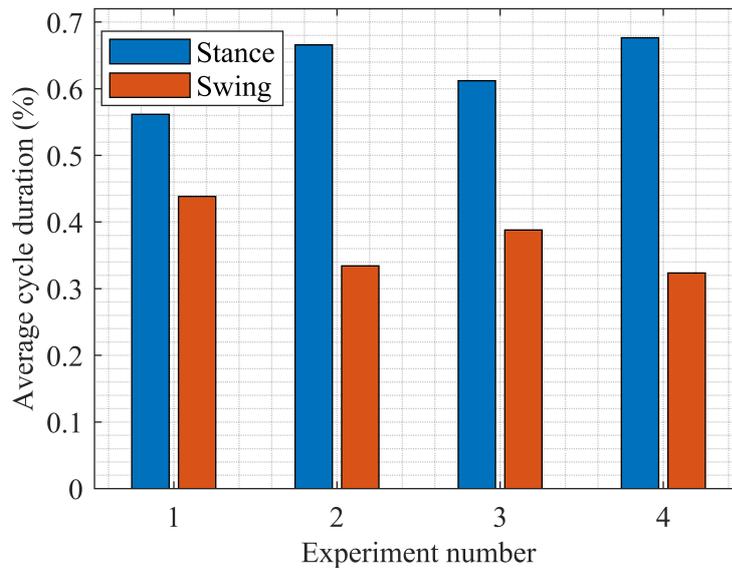
Figure 5. Average cycle duration percentages for the gait phases across all experiments.

performed peaks in the FSR signals earlier in the gait cycle than misaligned configurations, highlighting knee exoskeleton alignment's influence on force application timing. As walking speed increases, the FSR signals' variation lessens, particularly in misaligned configurations, implying smoother force application at higher speeds and more noticeable effects of misalignment at slower speeds.

The deltas and ratios were computed to find sensitive metrics that quantify the joint misalignment. Negative delta values indicate which robot or human is ahead during a movement. A ratio close to 1 indicates good alignment, while a ratio close to 0 indicates a significant discrepancy between signals used to compute the ratio. As can be seen in Figure 4, the largest discrepancies and lowest ratios often occurred in Experiment 4 (Misaligned with Speed 2 m/s), this experiment presented the longest stance and shortest swing phase, suggesting that misalignment combined with a high speed may extend stance duration while reducing swing duration. Conversely, smaller differences and higher ratios typically correspond to aligned configurations at slower speeds.

5. Conclusions

This work developed here proven to be effective for studying the effects of misalignment and interaction forces in physical Human-Robot Interaction (HRI). The results showed that misalignment level and walking speed significantly influence robot assistance effectiveness and gait cycle phases duration. These results have important implications for novel design in rehabilitation robotics where a thorough understanding of misalignment effects can enhance system safety, user comfort and controller performance. Future work should include more complex scenarios where the human-robot interactions takes place and where controller designs can use this approach for yielding be more effective strategies. Petersen *et al.* (2020)

6. ACKNOWLEDGEMENTS

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