Evaluation of Lower Limb Exoskeleton for Improving Balance during Squatting Exercise using Center of Pressure Metrics

Sruthi Ramadurai[1], Michael Jacobson[1], Prakyath Kantharaju[1], Hyeongkeun Jeong[1], Heejin Jeong[1,2], and Myunghee Kim[1]
[1]University of Illinois at Chicago, [2]Arizona State University

The foot center of pressure (COP) variability is an important indicator of balance, particularly relevant for rehabilitation and training using wearable lower limb exoskeletons. This study aimed to evaluate the effectiveness of our exoskeleton in assisting squatting motion using the COP variability as a metric. Six human subjects performed alternate squatting and standing movements while their foot pressure and COP trajectories were recorded using insole pressure sensors. The exercises were performed under three conditions: i) no device, ii) unpowered device, and iii) device with optimal stiffness. Results showed that the variability of the COP trajectory in the anterior-posterior direction of the foot during squatting tended to be lower for the optimal stiffness condition than the no device and unpowered device conditions, indicating the potential usefulness of the device in improving balance during squatting. This study has implications for human-in-the-loop optimization and balance control of the exoskeleton based on COP.

INTRODUCTION

Squatting exercises are frequently used in resistance training and rehabilitation to help people recover from injuries to their lower extremities (McGinty, Irrgang, & Pezzullo, 2000; Yu, Kumar, Turk, & Liu, 2019). Squatting is a symmetric bilateral exercise, which can be used to strengthen muscles on one or both sides of the body, depending on patient needs (Luo et al., 2021). Perhaps, squat exercise can be further motivated with a reliable lower extremity exoskeleton, instead of human aids. Such exoskeletons typically employ model-based control methods as balance controller designs (Shi, Zhang, Zhang, & Ding, 2019; Xiong, 2014). Such methods, however, are not very robust against large and unexpected perturbations caused by human interactions (Luo et al., 2021). In other words, unpredictable human-exoskeleton interaction forces and perturbations may cause conventional balance controllers to operate unreliably.

Considering the unknown human-robot interaction forces, researchers have used physiological signals to control the exoskeleton. Muscular activation and metabolic cost have been used as metrics of energy consumption (Di Natali et al., 2019; Park, Park, & Kim, 2017; Z. Wang et al., 2021), whereas center of pressure is an indicator of balance, which is important for patient populations and older adults (Karst, Venema, Roehrs, & Tyler, 2005; Li, Liang, Wang, Sheng, & Ma, 2016; Mettler, Chinn, Saliba, McKeon, & Hertel, 2015; Ruhe, Fejer, & Walker, 2011). Sado, Yap, Ghazilla, and Ahmad (2019) designed a wearable lower-body exoskeleton to assist repetitive load-lifting and manual-handling tasks and its evaluation was based on muscle activation as a metric. Y. Wang, Zhao, Diao, Feng, and Li (2021) designed a semi-active exoskeleton that reduced muscle fatigue of the lower limb while squatting. The device was evaluated based on muscle activity, metabolic cost and plantar pressure. Yan et al. (2021) developed a lightweight, wearable, and passive lower-limb exoskeleton that acts as a chair for workers, allowing them to squat for extended periods of time. Ergonomic assessments of muscle activity, plantar pressure, endurance time, and comfort were done to evaluate the passive device.

Balance-related measures can also be used to control the robot, such as the foot center of pressure (COP) metrics (S.-H. Lee & Goswami, 2012). Therefore, obtaining the foot COP information directly and precisely is highly desirable. Luo et al. (2021) discussed findings from their study on a lower extremity exoskeleton with force sensors on each foot for precise COP measurement. They explored the concept of a reinforcement learning based robust controller that encourages the COP to stay inside a stable zone when subjected to the uncertainty of human interaction forces. The evaluation study of the controller showed its ability to perform well-balanced squatting motion under realistic human interaction. However, their evaluation method was limited to numerical experiments only. Jeong, Woo, and Kong (2020) developed an exoskeleton for squat lifting that uses a balance control method based on location of the COP for assisting the squatting motion. In a preliminary test on a human subject, the amplitude of the COP was shown to be lower for the balance control approach compared to the body weight support method for one participant.

In this study, we conducted a secondary data analysis of the human-in-the-loop optimization of the exoskeleton parameter to minimize squat efforts. The algorithm, human-in-the-loop optimization, has been applied to various wearable devices, soft hip exosuit (Ding, Kim, Kuindersma, & Walsh, 2018), hip and ankle exosuits (Kim et al., 2019), ankle-foot prosthesis (Wen, Jacobson, Zhou, Chung, & Kim, 2020), and now ankle-foot orthosis (Kantharaju et al., 2022). Hence, this algorithm is not device specific and also not activity specific. Such human-in-the-loop optimization methods have been applied for walking (Ding et al., 2018; Kim et al., 2019; Wen et al., 2020), running (Zhang et al., 2017) and squatting (Ding et al., 2018). In addition, we used the two-degree-of-freedom robotic ankle exoskeleton end-effector built by our lab to test various activity scenarios (Jacobson & Kim, 2021). The exoskeleton was built for not only squatting, but also walking, running, and standing balance, where we successfully optimized parameters in our study. We evaluated the effectiveness of our lower limb exoskeleton in improving squatting balance based on center of pressure as a metric and involving multiple human subjects. We used COP variability, or the standard deviation of the COP trajectory in the anterior-posterior and medial-lateral directions, as the main balance-related metric as it has been found to be a reliable and consistent measure of postural equilibrium (Geurts, Nienhuis, & Mulder, 1993; Le Clair & Riach, 1996; Palmieri, Ingersoll, Stone, & Krause, 2002; Quijoux et al., 2021). A decreased value for this measure indicates an increased ability to maintain postural control. Our specific aim is to compare the differences in COP variability among three squatting conditions: i) while not wearing the exoskeleton, ii) while wearing the exoskeleton in unpowered condition, and iii) while wearing the exoskeleton in optimal stiffness condition.

METHOD

Experimental protocol

Ten healthy male subjects (age = 24.6±4.0) were recruited for the study. The study protocol (IRB #2020-0563) was approved by the Institutional Review Board at the University of Illinois at Chicago. The subjects wore a tethered ankle exoskeleton on their dominant leg. The exoskeleton was powered by two off-board actuators (Humotech, PA, USA) utilizing a Bowden cable system. Embedded within the ankle exoskeleton were magnetic encoders and tension load cells which sensed ankle angle and torque, respectively. For our control architecture we utilized an impedance controller with two stiffness parameters, $K_{ascending}$ and $K_{descending}$, to tune the assistive torque of the exoskeleton during the ascent and descent of the squatting movement. The experimental setup for the study is shown in Figure 1.

On the first day, the subjects underwent an acclimation period to familiarize themselves with the emulator system. The squatting study during the acclimation period lasted for 80 minutes, in which the squatting exercise was performed for a total duration of 20 minutes, with periods of rest in between. On the second day, human-in-the-loop (HIL) optimization of stiffness parameters and validation of those parameters were conducted. For each trial of the validation study, the subjects were instructed to perform alternate squatting and standing for a total duration of 4 minutes. The squat cycle consisted of a descending motion and ascending motion that lasted approximately 1 second each. The squat was followed by a resting period of 6 seconds in the standing position and a metronome was played to control the subject's squat frequency. The subjects performed the squatting exercise in three conditions:

1. While not wearing the exoskeleton.
2. While wearing the exoskeleton in unpowered condition.
3. While wearing the exoskeleton with optimal stiffness determined through HIL optimization.

The foot pressure data obtained from the subject during the optimal stiffness condition was compared with the data obtained during the unpowered device and no device conditions.

Pressure measurement

In this study, we used the F-scan insole pressure sensor (Tekscan, MI, USA) to collect the pressure data. The insoles were trimmed to fit and placed within the right and left shoes of the subject. Sensor placement was above the insole of the subject's shoe. To collect the data, a standard step calibration was conducted first, which calibrated the pressure data for each subject and the sampling rate was set to 50 Hz. After the calibration, data collection of foot pressure for our experimental protocol ensued.

Data Analysis

Based on visual inspection of data quality, six subjects' data were considered for analysis in this pilot study. For each subject, the foot pressure time series data was filtered with a low pass filter at 2 Hz cut-off frequency. For all the conditions, the last 110 seconds of the squatting exercise were considered for analysis. The initial squats were left out from the analysis to control for adaptation effects. The squat onsets and squat phase were determined from the peaks in the pressure signal. The y-COP and x-COP data were filtered using 2 Hz low pass filters. The trajectories of y-COP and x-COP during the squat phase were averaged in the time domain and their standard deviations were calculated (shown in Figures 2 & 3) from a representative subject. The average standard deviations of the y-COP and x-COP trajectories were the key outcome measures as they have been found to be important indicators of balance (Palmieri et al., 2002). The subjects wore the exoskeleton on their right foot. The pressure data from the right foot, therefore, will directly reflect the effect of ankle-foot assistive torque on the pressure (device side), rather than the change in the participant's posture. The pressure data from the other foot (left foot), however, will show the change in the subject's squat pattern when given assistance. Hence, we conducted the analysis using the pressure data from the left foot. That is the reason Figures 2 and 3 depict the pressure map of the left foot.

The Kolmogorov–Smirnov test was used to check the normality of the outcome data distributions, with significance level $\alpha = 0.05$. After verifying normality, the statistical comparison of the outcomes between the three conditions (optimal stiffness, unpowered and no device) was performed using the paired student's t-test, with significance level $\alpha = 0.05$.

RESULTS

Average trends

Figure 4 presents that the average standard deviation of the y-COP trajectory tends to be higher for the unpowered device condition when compared to the no device condition and optimal condition by 22% and 27%, respectively ($p>0.05$).

The average standard deviation of the x-COP trajectory was higher for the unpowered device condition compared to the no-device and optimal stiffness conditions by 20% and 8% ($p>0.05$), respectively (See Figure 4).

The time averaged center of pressure trajectories observed during the squat cycle for the three different conditions are shown for a representative subject in Figures 2 and 3. Figure 2 shows the x-COP trajectory (the medial-lateral movement of the COP) and Figure 3 depicts the y-COP trajectory (anterior-posterior movement of the COP).

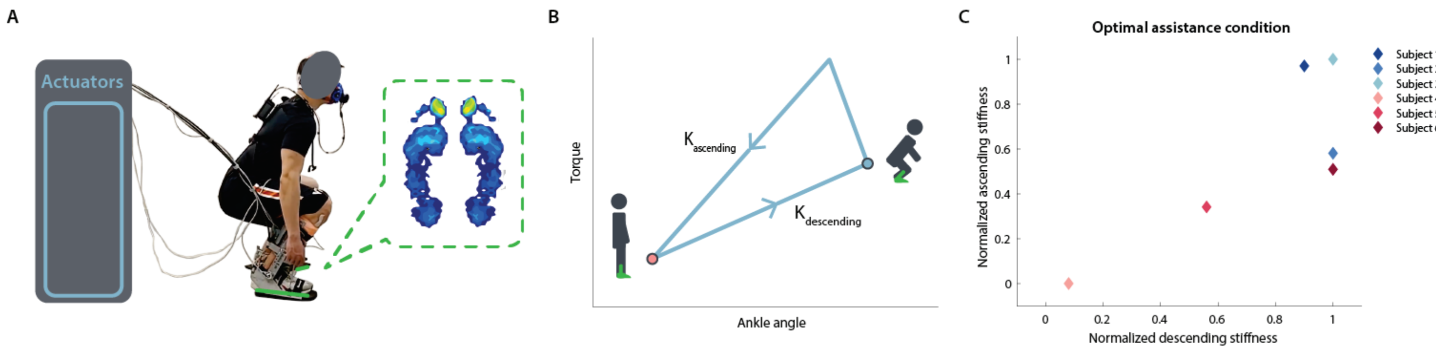

Figure 1. Experimental setup of squatting optimization study including desired torque trajectory and optimization results. **(A)** Detailed experimental setup image including off-board actuators in grey, foot pressure sensors and placement in green, and human subject wearing ankle exoskeleton on dominant leg. **(B)** Ankle angle and desired torque trajectory for squatting exoskeleton control. The $K_{ascending}$ parameter is the proportional stiffness when the subject is ascending from the the bottom position of the squat and $K_{descending}$ is the proportional stiffness when the subject is descending into the bottom of the squat. **(C)** The optimal stiffness parameters from each subject as a result of HIL optimization

COP variability in the medial-lateral direction

Figure 2 shows that the average standard deviation of the x-COP trajectory was higher for the unpowered device condition compared to the no-device and optimal stiffness conditions by 116% and 79% ($p>0.05$), respectively. The x-COP variability for the optimal stiffness condition is lower compared to unpowered device condition but higher in comparison to the no device condition.

COP variability in the anterior-posterior direction

From Figure 3, it is observed that the average standard deviation of the y-COP trajectory tends to be higher for the unpowered device condition when compared to the no device condition and optimal condition by 100% and 120%, respectively ($p>0.05$). The unpowered condition led to the largest variability in the y-COP trajectory. The y-COP variability for the optimal stiffness condition is the lowest of the three.

DISCUSSION

In this paper, we have performed secondary data analysis of human-in-the-loop optimization of exoskeleton parameters to minimize physical effort during squatting (metabolic cost reduction). The optimal assistance has been provided for various activities such as walking (Ding et al., 2018; Gordon, McGreavy, Christou, & Vijayakumar, 2022; Li et al., 2020; Song & Collins, 2021; Zhang et al., 2017), and running (G. Lee et al., 2017; Miller, Tan, Farina, Sheets-Singer, & Collins, 2022; Uchida et al., 2016; Zhang et al., 2017) to minimize metabolic cost (For a review, see (Sawicki, Beck, Kang, & Young, 2020)). In this study, in addition to the metabolic cost of squatting, we examined the foot pressure, and it appears that the balance can be influenced for some subjects.

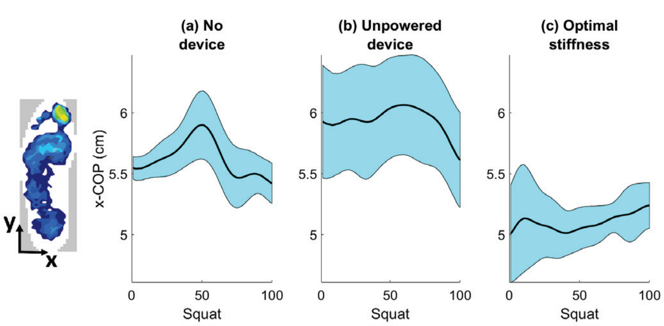

Figure 2. Time averaged x-COP trajectory (center of pressure movement in the medial-lateral direction) during the squat for (a) No device, (b) Unpowered device, and (c) Optimal stiffness conditions

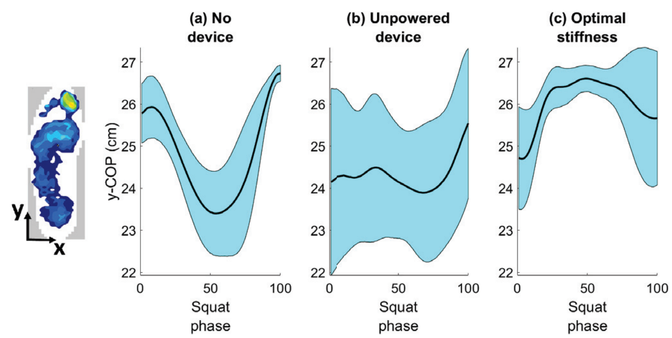

Figure 3. Time averaged y-COP trajectory (center of pressure movement in the anterior-posterior direction) during the squat for (a) No device, (b) Unpowered device, and (c) Optimal stiffness conditions

The key finding of this study is that the variability of the COP trajectory in the anterior-posterior direction during squatting tends to be minimized while wearing the assistive device with the optimal stiffness, determined through human-in-the-loop optimization (Wen et al., 2020). Larger variability in the COP trajectory has been associated with poorer ability to maintain balance (Abrahamova & Hlavačka, 2008). In this study, the y-COP variability for the optimal stiffness condition tended to be lower in comparison to the no device and unpowered device conditions, indicating the usefulness of the exoskeleton in improving balance during squat exercises. The variability of the x-COP trajectory for the optimal stiffness condition tended to be higher relative to the no device condition, but lower in comparison to the unpowered device condition.

The increase in variability of the x-COP and y-COP trajectories while squatting with the unpowered device could be due to the eccentricity in the center of gravity caused by wearing the exoskeleton, which creates an imbalance. This entails additional effort from the subject to maintain the balance of the body (Jeong et al., 2020). Such an increase in the variability of the COP trajectories while wearing the unpowered exoskeleton suggests that in the ankle joints, there had been active dorsiflexion and plantar flexion activities. Previous research has shown

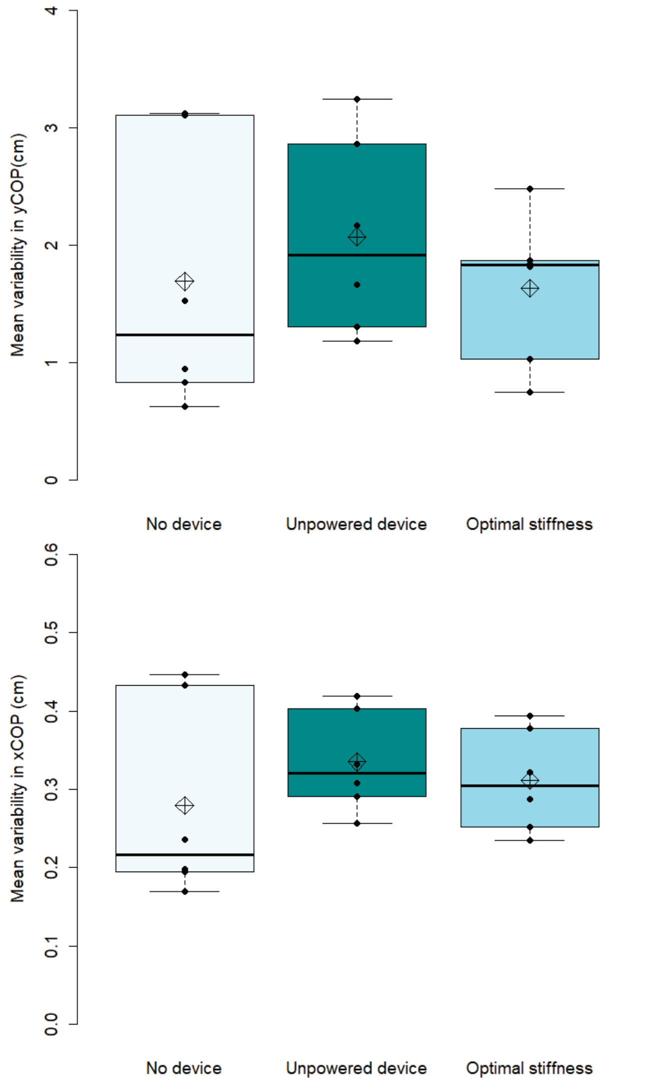

Figure 4. Mean variability (standard deviation) in the y-COP (top) and x-COP (bottom) trajectories for 6 subjects

that the effort to regain balance after wearing the exoskeleton manifests as increased muscle energy consumption (Herman, Cook, Cozzens, & Freedman, 1973). The human-in-the-loop optimization method could help to overcome this problem by providing torque based on the optimal stiffness for each subject and assisting the subject to maintain balance after wearing the exoskeleton.

Limitations: The study was limited in its sample size and statistical power. More subjects need to be recruited in order to provide conclusive evidence of balance improvement while wearing the exoskeleton with optimal stiffness. Another limitation was that for certain subjects, the signals from the foot pressure sensor were noisy and lacked clear pressure waveforms that are typically seen during squatting movements.

Future work: For our future work, we plan to conduct the evaluation study with a larger sample population. We also want to perform human-in-the-loop optimization studies based on COP variability.

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