Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 56-3 (2023) 163–168

Knee Stiffness in Assistive Device Control at Quiet Stance: A Preliminary Study

Gayatri Sreenivasan * **Chunchu Zhu** ** **Jingang Yi** **

* *Department of Electrical and Computer Engineering Rutgers University, Piscataway, NJ 08854 USA (e-mail: gs912@scarletmail.rutgers.edu)*

** *Department of Mechanical and Aerospace Engineering Rutgers University, Piscataway, NJ 08854 USA (e-mail: {cz373,jgyi}@rutgers.edu)*

Abstract: The paper explores the use of knee stiffness as a parameter in the design of wearable knee assistive devices for augmenting human postural balance. The knee moment-angle relationship is utilized to estimate the quasi-stiffness of the knee. The measurement methods are carefully chosen to be non-invasive without rigid joint attachment to allow observation of unimpeded quiet stance. The relationship between identified biomechanical parameters and computed stiffness estimates is analyzed, and the resulting estimates are employed in the controller design of a stiffness-based knee assistive device. The paper also investigates the biomechanical response of the human body to the modulation of applied stiffness in the presence of varied visual stimuli. This research is a crucial first step toward designing knee-based assistive devices to enhance human postural balance in destabilizing environments.

Keywords: Knee Joint Stiffness, Knee Wearable Assistive Device, Quiet Standing

1. INTRODUCTION

Industrial workers often perform repetitive tasks that involve repeated gait sequences, such as squatting and kneeling, which can cause knee joint stress and lead to work-related musculoskeletal disorders (WMSDs) such as knee osteoarthritis, knee injuries, and chronic knee pain. To prevent WMSDs and maintain worker health, safety, and productivity, wearable knee assistive robots (WKARs) have been developed (Chen et al. (2021)). Recently, gait-switching controllers have been introduced for WKARs to provide assistance to workers during sequences involving multiple gaits (Zhu et al. (2022)). However, current gait-switching controllers are limited in their operation when the human is at quiet stance, which is a common gait carried out by workers and most gait sequences involve a stance phase. Moreover, while quiet standing is relatively easy for humans, it becomes more challenging in dangerous and perturbing occupational environments, leading to high fall risk and fatalities in construction workers (Cleworth et al. (2012)). To provide a complete cycle of support to the worker and mitigate fall risk, it is essential to focus on the development of balance enhancement controller design for advanced WKARs. However, current research and literature on balance supporting WKAR design are limited. Knee joint stiffness is an important biomechanical parameter that contains information about the natural balance and posture of a human. During unimpaired natural standing gait, limb stiffness is modulated to improve postural balance and minimize damaging impacts on varying terrains. The muscles surrounding the knee joint are engaged to stiffen the joint by alteration of reflex behavior or modification of intrinsic muscle properties. Incorporating joint stiffness as a parameter in WKAR controller design is crucial for designing balance controllers for WKARs. However, there are currently no known procedures for measuring knee stiffness during quiet standing, which can be attributed to the complexity of prior stiffness quantification experiments and associated practical challenges.

Previous joint stiffness estimates have been obtained either via direct estimates using perturbation methods or electromyography (EMG) based model estimates (Nalam et al. (2020), Pfeifer et al. (2012)). While these techniques can perform well for gaits with more significant motions like kicking or sitting, they can interfere with the human body's natural behavior during quiet standing, resulting in altered gait and inaccurate results. Therefore, it is important to introduce experimental protocols for knee joint stiffness quantification that are well suited for quiet standing gait analysis to propel balance augmenting WKAR design. It should also be noted that WKARs have the potential to provoke postural instability in users if their design does not take into account the changes in human gait induced by the presence of the device and the environment encountered (Beck et al. (2023)). In quiet standing, for instance, these variables can significantly impact the chosen balance strategy and associated biomechanical behavior.

The main contribution of this study was (i) to find a method to estimate the natural knee joint stiffness of humans at quiet stance and (ii) to study the change in

* Gayatri Sreenivasan and Chunchu Zhu equally contributed to this work.

** This work was supported in part by US NSF awards CMMI-1762556 (Yi) and DGE-2021628 (Sreenivasan). Address all correspondence to J. Yi.

10.1016/j.ifacol.2023.12.018

human quiet stance under WKAR-applied stiffness modulation and destabilizing visuals. The former specifically involved quantifying the natural knee joint stiffness during quiet standing, validating the knee joint stiffness measurement strategy, identifying biomechanical factors affecting the knee joint stiffness estimates, and understanding the relationship between the identified factors and knee joint stiffness. The latter entailed a series of experimental trials that employed bilateral wearable knee exoskeleton with a stiffness-based control mechanism to provide assistive torque. The controller was run at different applied stiffness parameter settings. To create a more dynamic response to the WKAR controller in line with what a construction worker would experience, virtual reality (VR) was used to immerse the subjects in a destabilizing occupational environment. Various biomechanical parameters are analyzed to gain insight into the effects of the changing stiffness controller settings on human balance at quiet stance. Thus, the study aims to build a foundation of knowledge regarding knee joint stiffness during quiet standing gait for postural balance enhancement research.

The paper is organized as follows. Section 2 provides a clear definition of knee joint stiffness in this study. Section 3 explains the experimental design. The experimental results are presented in Section 4, followed by further examinations in Section 5. We conclude our study in Section 6 and propose some related open research problems.

2. KNEE JOINT STIFFNESS

Measurement of human knee joint stiffness poses practical challenges due to its complex multi-degree of freedom system. Knee joint stiffness is difficult to define because it is influenced by several factors, including muscle activity, joint alignment, and ligament and cartilage integrity. These factors vary between individuals and over time, making it challenging to compare results across studies. Different methods, such as passive, active, or isometric testing, can yield different measurements of knee joint stiffness. Given the vast and diverse terminology and testing methods surrounding knee joint stiffness, it is essential to clarify the definition of the term 'stiffness' used in this work. The usage of the term stiffness in biomechanical studies has generated much discussion regarding the distinction between physiological stiffness and other measures referred to as stiffness (Latash and Zatsiorsky (1993)).

This study uses a moment-angle technique to measure knee stiffness during quiet standing. This approach is preferred due to its ability to preserve the natural posture and sway of the subject. Such studies measure the quasi-stiffness of the joint. Quasi-stiffness is not measured at equilibria and represents the system's resistance to external forces while ignoring the timing of displacement (Latash and Zatsiorsky (1993)). This method allows for minimal sensors and does not require fixing the joint, avoiding the potential for altered gait and inaccurate results. Even though the moment-angle provides the advantage of unhindered gait, it is an active testing method, and care has to be taken while computing the stiffness estimates due to the small variation in the magnitude of moment and angle during quiet stance.

The knee angle θ_k is defined as the relative angle between the thigh and shank segments (see Fig. 1(a)), and the human applied knee moment is denoted as $M_k(t)$. Knee joint stiffness $K_k(t)$ is then defined as:

$$K_k(t) = \left| \frac{M_k(t)}{\theta_k(t)} \right|, \tag{1}$$

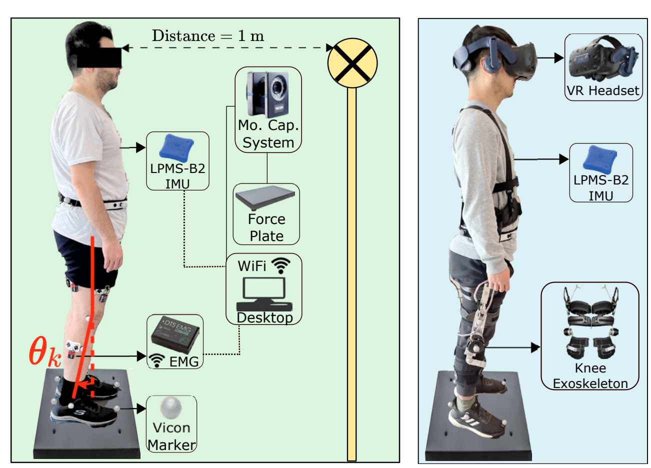
where $K_k(t)$ is the quasi-stiffness of the knee joint, which we refer to as the stiffness of the knee joint in this study. The definition of knee angle was chosen specifically as the active stiffness present at the knee joint during quiet standing is small in magnitude. Using a definition of knee angle that results in a large magnitude of the denominator of Eq. (1) makes the stiffness values computed even smaller, and is hence avoided. To study the magnitude of stiffness variation, we use the absolute value of stiffness. The definition of knee angle used in this study is similar to that used in locomotion and WKAR studies, and the torque-angle relationship is often used to analyze and tune the device controller, allowing for easy translation of knee stiffness definition across WKAR studies for different gaits.

3. EXPERIMENTAL DESIGN

The experiments were divided into two sets - (i) the quantification of knee stiffness during quiet stance and (ii) the study of effects of a stiffness-controlled WKAR on quiet stance.

3.1 Quantification of Natural Knee Joint Stiffness

Seven young subjects participated in the study (4 female, 3 male, weight: 62±14 kg, height: 167±8 cm, age: 25±3 years). All participants self-reported to be able-bodied and healthy. The subjects were informed of the experimental protocol and provided consent. All test procedures were approved by the Institutional Review Board (IRB) at Rutgers University. The experimental setup, shown in Fig.1, includes sensors, equipment, and communication among them. Subjects were required to maintain quiet stance for 80 seconds, gazing at a target atop a pole. The force plate (Bertec Corp.) recorded ground reaction forces (GRF) and center of pressure (CP) data at a 1000 Hz sampling rate, while a motion capture system (9 vantage cameras, Vicon, Ltd.) captured lower limb kinematic



(a) (b)

Fig. 1. Experimental setup for (a) quantifying knee joint stiffness at quiet stance and (b) studying effect of WKAR-applied stiffness modulation and destabilizing visuals on quiet stance.

data at 100 Hz. Joint angles were computed from motion capture data. OpenSim (Delp et al. (2007)) calculated inverse dynamics to obtain knee moment data. To measure muscle activation, five wireless surface EMGs (Noraxon, Inc.) were attached to selected muscles surrounding the knee (rectus femoris (RFEM), vastus lateralis (VLAT), biceps femoris (BFLH), semitendinosus (SEMT) and lateral gastrocnemius (LGAS)). Muscle activation measurements were recorded at 1500 Hz and synchronized with the knee moment and angle data. The data from two trials were analyzed per subject to establish the relationship between muscle activation and knee joint stiffness.

3.2 Exoskeleton Controller Design

In controlling knee exoskeletons, two widely-used methods are impedance and stiffness controllers. Impedance control provides a natural and compliant interaction between the exoskeleton and the user, enabling smoother and more coordinated movements. It is versatile, adjustable to different movement patterns and assist levels, but challenging to tune and may not offer direct control over joint torque. The impedance controller design is described as

$$\tau_e = k(\theta_k - \theta_e) - b\dot{\theta}_k, \tag{2}$$

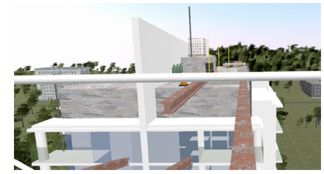
where τ_e represents the assistance torque, k denotes the stiffness constant, θ_k refers to the measured angle, θ_e represents the equilibrium angle, b indicates the damping coefficient, and $\dot{\theta}_k$ is the measured angular velocity.

Stiffness control is a simpler and more direct approach that allows direct control over joint torque, providing natural and human-like movement with fewer sensors and computations. It neglects the derivative term in Eq. 2 and generates continuous torque under varying walking speeds without the need for gait phase estimation. However, it may lack compliance and adaptability compared to impedance control and may require additional compensation mechanisms for unexpected disturbances. The work in Huang et al. (2022) proposes a comprehensive study of a continuous-phase stiffness-torque model for walking gaits, inspired by gait biomechanics. Our work only consists of the quasi-static stance phase, and we determine the optimal stiffness model parameters by collecting motion and ground reaction force data from our experiments.

3.3 Modulating Applied Stiffness Using Knee Exoskeleton

The second part of the experiment involved three subjects (2 female, 1 male, weight: 64±14 kg, height: 165±11 cm, age: 23±4 years) to investigate the effects of applied torques from the knee exoskeleton. The knee exoskeletons were built on quasi-direct drive (QDD) actuators with high-torque, high-backdrivability, and high-bandwidth features, enabling torque control based on knee joint angles (Zhu and Yi (2023)). The experiments were conducted with each subject being made to stand on a force plate for 80 seconds. The exoskeleton's stiffness-based controller in Eq.2 employed three sets of stiffness parameters: k1 = k_{st} (natural knee stiffness), k2 = 130% k_{st}, and k3 = 180% k_{st}. These values were calibrated for each subject in accordance with their natural stiffness values. Each subject performed 8 randomized trials: low- and high-elevation without the exoskeleton, and low- and high-elevation with the exoskeleton using the three sets of stiffness parameters. The experiment used an HTC Vive Pro VR headset to

(a)



(b)

Fig. 2. Virtual reality scenarios at (a) low-elevation environment and (b) high-elevation environment.

provide visual and auditory stimulation, with VR scenes of low- to high-elevation construction sites and gusts of wind corresponding to the elevation level as shown in Fig. 2.

The GRF and CP data were used to analyze postural sway and compute the variation of intersection point (IP) height with frequency (Boehm et al. (2019)). To avoid noisy data, the first and last 5 seconds of the processed data were trimmed. The sway data was plotted as CP_y versus CP_x to represent the anterior-posterior (AP) and medial-lateral (ML) directions respectively. Analysis was performed by plotting 95% prediction ellipses to encompass 95% of the dataset. An IMU (LP-RESEARCH Inc.) was also strapped to the subject's torso to collect trunk linear acceleration measurements. The measured accelerations were used to determine the 95% prediction ellipse area of acceleration variations in the AP and ML directions.

4. EXPERIMENTAL RESULTS

In this section, we present the experimental results on knee stiffness during natural stance and analyze subjects' responses to WKAR-applied torques under destabilizing visuals.

4.1 Natural Knee Joint Stiffness

The knee joint stiffness was computed using Eq.(1) from the processed knee moment and knee angle data. The resulting stiffness trajectories are displayed in Fig.3. Across subjects, stiffness values ranged from 0.1 Nm/(kg·deg) to 1.03 Nm/(kg·deg), and gender did not correlate with stiffness. As stiffness remained relatively constant over time, the mean of the stiffness signal was calculated for each trial. Table 1 summarizes the results obtained from the multi-subject trials, showing a range of mean stiffness values from 0.0276 Nm/(kg·deg) to 0.9179 Nm/(kg·deg).

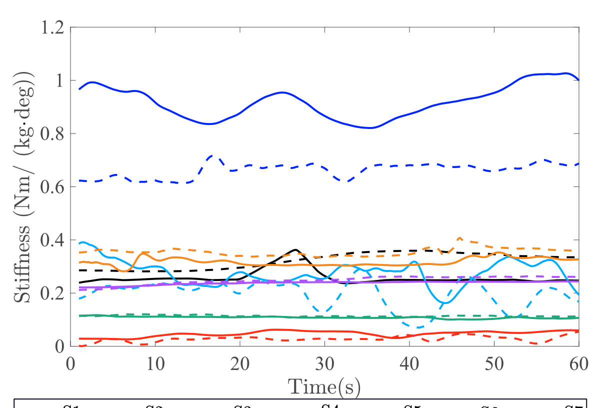


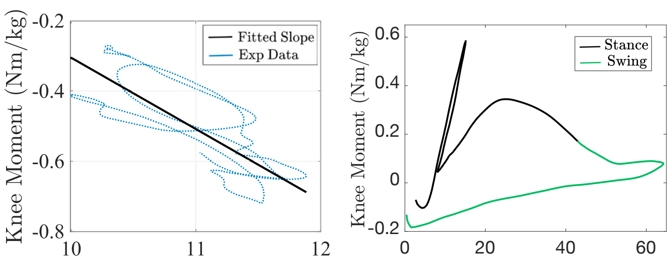
Fig. 3. Knee stiffness trajectories for all subject trials. Solid lines indicate the first trials and the dashed lines indicate the second trials.

Table 1. Stiffness Values Across Subjects

Subject	Mean Stiffness in Nm/(kg·deg) (Trial 1, Trial 2)
1	(0.0470, 0.0276)
2	(0.2590, 0.3220)
3	(0.2764, 0.1969)
4	(0.9179, 0.6620)
5	(0.1082, 0.1138)
6	(0.3171, 0.3549)
7	(0.2379, 0.2483)

Table 2. Slope of Moment-Angle Plots

Subject	Slope of Moment-Angle Plot (Trial 1, Trial 2)
1	(-0.2033, -0.2214)
2	(-0.0304, -0.0572)
3	(-0.2595, -0.3638)
4	(0.2323, -0.0282)
5	(-0.0807, -0.0777)
6	(-0.1689, -0.1468)
7	(-0.2625, -0.2737)



(a) (b)

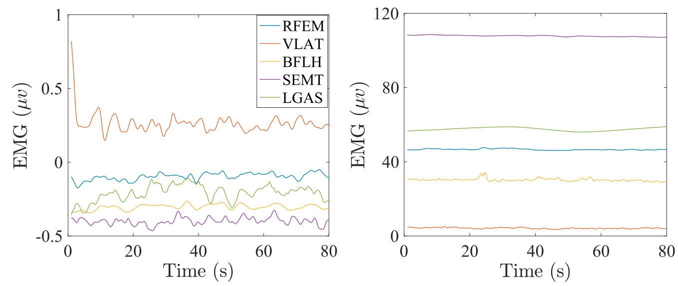
Fig. 4. Knee moment-angle plots: (a) quiet standing (b) stance phase of walking.

While stiffness values remained consistent for the same subject across trials, significant variation was observed between subjects, and there was no direct correlation between subject weight and computed knee stiffness values.

Fig 4(a) shows the knee moment-angle plot for quiet standing, while Fig 4(b) presents the plot for the stance and swing phase during walking (Huang et al. (2022)). The slope of this plot is often used to define stiffness in dynamic gait studies. Although the slopes' magnitudes are similar for both gaits, the moment's direction differs, as indicated by the moment's sign. Table 2 tabulates the slope values for each quiet standing experimental trial for analysis. The slopes' values are very similar for the trials of the same subject, but they vary significantly across different subjects. This trend holds for six out of the seven subjects' experimental data. The slope of the absolute knee moment-angle plot for quiet standing yields a positive value in all test cases because knee excursion causes the knee angle to increase. Consequently, the knee moment's absolute value increases to enhance postural stability. In most cases, the natural knee excursion takes place in the positive AP direction, resulting in a negative moment applied to maintain postural stability by changing the displacement's direction. Therefore, the moment-angle graph has a negative slope as the moment is actively provided when the human exceeds the bounds for standing stability.

Table 3. (Mean Sway Area (mm^2), Mean Acc. Area ($(\frac{cm}{s^2})^2$)) Comparison

Case	Low Elevation	High Elevation
No WKAR	(841, 19.67)	(376, 21.00)
WKAR $k = k1$	(516, 7.23)	(510, 5.91)
WKAR $k = k2$	(620, 5.31)	(536, 10.47)
WKAR $k = k3$	(451, 7.51)	(572, 6.83)



(a) (b)

Fig. 5. EMG signals to measure muscle activation (a) when subject is relaxed and (b) when subject is rigid.

4.2 Factors Affecting Natural Knee Joint Stiffness

By calibrating a baseline per subject, active stiffening of muscles can give information regarding when postural changes occur as an observable reaction, when they cannot not be tracked by motion capture measurements. For example, Subject 4 Trial 1 exhibited a positive moment-angle slope attributed to the subject assuming a tensed posture, with minimal knee excursion and high muscle activation surrounding the joint. This is supported by the relatively high values of the EMG signal (Fig.5(b)) as compared to all other experimental cases (Fig.5(a)). The computed mean knee stiffness magnitude is also much higher in this trial compared to other cases, as seen in Table. 1. Thus, the sign of the slope of the moment-angle curve, along with muscle activation and knee excursion can provide insight into whether the subject's posture and joints are tensed up and rigid or relaxed.

Studying the CP shift in relation to stiffness values can reveal the range beyond which joint stiffening occurs in response to fall risk. While ankle torque and body sway significantly influence the CP data, research indicates that the joints operate synergistically to counteract excessive sway and maintain balance. Analysis of knee stiffness reveals that a rigid subject (stiffness = 0.9179 Nm/(kg·deg)) experiences less sway, while a relaxed subject (stiffness = 0.0276 Nm/(kg·deg)) experiences more sway, as shown in Fig. 6(a).

4.3 Effect of Varied WKAR-Applied Stiffness

The sway area was calculated for different cases of elevation while varying the applied stiffness. One-way ANOVA tests were used to determine the mean sway area across subject trials. Table 3 summarizes the mean sway area obtained for various testing cases. Results show that introducing the WKAR significantly decreased the sway area for low-elevation cases (Fig. 6(b)), as expected. High-elevation visuals without the WKAR resulted in limited sway due to the subjects' conscious effort to protect themselves (Fig. 6(c)). Interestingly, the sway area decreased in most subject trials when visual stimuli changed from low- to high-elevation scenes. On the other hand, introducing

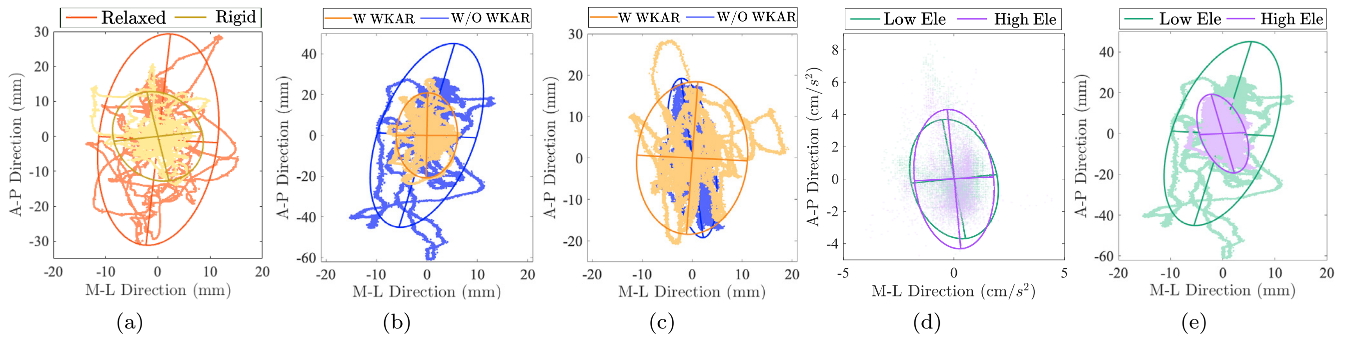


Fig. 6. Experiment results of 95% ellipse of (a) postural sway for a rigid subject compared to a relaxed subject; (b) postural sway data at low elevation with and without WKAR; (c) postural sway data at high elevation with and without WKAR; (d) trunk linear accelerations in AP and ML directions at low and high elevation; (e) postural sway data without WKAR at low and high elevation.

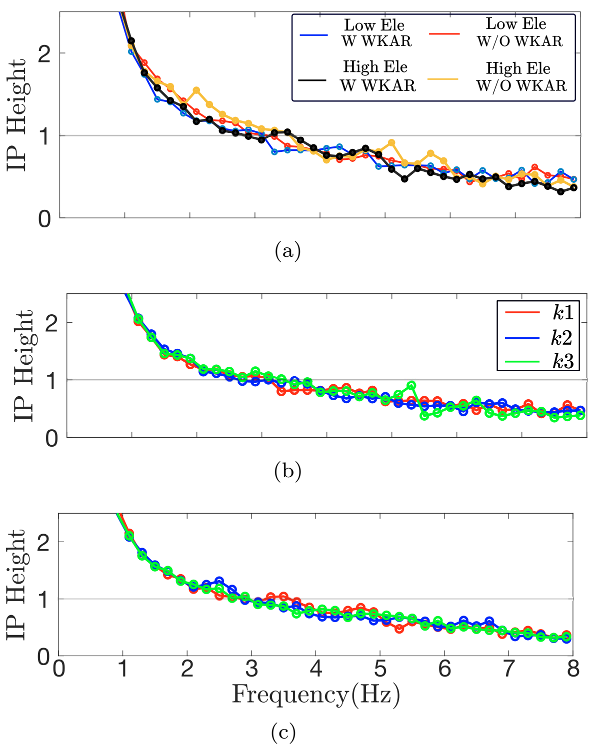


Fig. 7. IP height comparison at (a) low- and high-elevation with/without WKAR; (b) low-elevation under 3 sets of k; (c) high-elevation under 3 sets of k.

the WKAR increased the sway area for high-elevation scenarios, providing additional support and enabling subjects to relax their stance. As stiffness increased, the sway area also increased for high-elevation visuals. However, the average sway was higher for $k = k2$ and limited for $k = k3$ for low-elevation cases. Further observing other biomechanical factors can confirm whether the limited sway at $k = k3$ is due to perturbation or support.

Table 3 shows the mean 95% prediction ellipse area of acceleration data obtained from one-way ANOVA analysis across subjects. Fig. 6(d) reveals that the variation in acceleration during sway is larger for the high-elevation condition without WKAR support than the corresponding low-elevation condition. This difference may be due to continuous corrective measures taken by subjects to maintain postural stability in fear of falls. Specifically, the postural sway accelerations spiked for the high-elevation condition with $k = k2$, indicating that the applied stiffness perturbed the subject. Overall, the $k = k2$ case elicited reactionary measures in the form of limited sway. Conversely, the postural sway accelerations decreased for the low elevation test case with $k = k2$. it is hypothesized that the spike in average postural sway is a tradeoff for maintaining the lowered mean acceleration values. This implies a more relaxed cognitive state where subjects do not attempt to stabilize themselves.

The IP height curves contain information regarding the neural balance control strategies that subjects employ during different test cases (Sreenivasan et al. (2023)). One-way ANOVA was employed to obtain the mean subject IP frequency curve for each test case, normalizing the IP heights with respect to the center of mass (CM) height. Introducing the WKAR in the low-elevation test case did not drastically change the IP frequency curves, whereas introducing it in the high-elevation test case smoothed the IP curve considerably (Fig 7(a)). Changes in the IP curve suggest that the chosen balance strategy varies. Hence, the subject's balance with the WKAR was more predictable and likely intentional. For the low elevation scenario, $k = k2$ did not indicate that subjects were stressed as the balance strategy remained unchanged (Fig 7(b)). Large spikes and dips for the case of $k = k3$ suggested that the subject had to alter their balance strategy to maintain balance. For the high elevation scenario, increasing the WKAR-applied stiffness made the IP curve smoother (Fig 7(c)), indicating that while high WKAR-applied stiffness is perturbing in a relaxed environment, it is a welcome support in a destabilizing setting.

4.4 Effect of Varying Visual Stimuli

Higher elevation on whole led to smaller sway than lower elevation cases which is due to a desire to maintain better postural stability in the presence of visual threat (see Fig. 6(e)). Without WKAR support, the visual stimuli produced opposing extreme values of sway area. The WKAR support made the postural sway area comparable regardless of the visual stimulus with the average magnitude in between the two extremes. The postural sway accelerations increased from the low elevation to high-elevation case in the absence of WKAR support. The IP frequency curves showed more spikes for the high elevation test case (Fig 7(a)). Such spikes indicate that the balance strategy shown by the human is altered and that the ankle strategy is more heavily favored. The ankle strategy in this situation involves the body acting like a single inverted pendulum to stabilize the head, the source of the perturbing visuals. Thus, such a strategy is concluded to be a stabilizing reaction to the destabilizing visuals.

Table 4. Summary of Hypotheses

Case	Sway Ellipse Area	Acceleration Variation
Relaxed Reaction	Higher	Lower
Stressed Reaction	Lower	Higher
Fatigued State	Higher	Higher

5. DISCUSSION

This study considered the intricacies of joint stiffness definition and computation. Constructing a methodology to compute knee stiffness was complicated due to the sensitive nature of quiet standing. Established protocols that were deemed disruptive were avoided. The stiffness definition in this study was kept simple and the values obtained reflected the experimental protocol. Results show that knee joint stiffness during quiet stance is dependent on an individual's body structure, but remains consistent for that individual. Multiple trials are recommended to ensure consistency and confirm a relaxed stance scenario. Obtaining additional information on muscle and tendon characteristics could enhance our understanding of knee joint stiffness modulation in humans. Since current methods and sensors available to estimate physiological stiffness compromise the authenticity of standing, future research should focus on the development of lightweight wearable sensors capable of detecting biological signals related to knee joint stiffness without hindering natural postural sway.

Since the number of subjects in this study was limited, a larger sample size of subjects can shed light on whether knee stiffness has any correlation with gender, weight or age. An additional set of experiments were conducted with 12 test cases to investigate a greater number of WKAR-applied stiffness values. A single subject was enrolled in the study (Male, 85 kg, 170 cm, 27 years). The biomechanical parameters experienced an increase in the final few trials of the randomized testing sequence, potentially due to subject fatigue. It is with this knowledge that the relative trends in Table 4 were hypothesized. A medium range of sway ellipse area suggests a less tense stance with good postural stability. A lower variation in acceleration values indicates better control and stability, while random deviations in acceleration indicate corrective measures being taken to combat postural instability. To encourage balance, additional support from WKAR can increase the sway ellipse area to some degree for subjects with cognitive loading. This gives the subjects security against fall risk and gives them confidence to sway more naturally while lowering body accelerations. However, the sway ellipse area should not be allowed to increase to values that could lead to fall risk. Such situations can arise if the WKAR perturbs the subject when they are stressed. There will be an onset of a series of physiological reactions in an attempt to achieve stability, only to be hindered by the WKAR. Thus, it is important to properly design and tune the future WKARs to allow physiological reactions of the wearer to remain unhindered in case of an emergency.

6. CONCLUSION

The study examines the use of knee joint stiffness in the area of postural balance. The results provide a basis for further research to develop balance-augmenting WKAR controllers that can support industrial workers in perturbing occupational environments and reduce WMSDs and fall-related fatalities. The study analyzes the relationship between knee joint stiffness and other biomechanical factors during quiet standing, which is a novel approach as knee joint stiffness is primarily used for dynamic gaits in wearable exoskeletons. The study utilized VR and a modulated stiffness parameter in the WKAR to analyze how it affects natural standing gait. The findings can be used to design postural balance controllers for patients with muscular disorders, gait-switching controllers that enhance balance, and controllers that account for disturbance-induced reactive physiological human responses.

REFERENCES

Beck, O.N., Shepherd, M.K., Rastogi, R., Martino, G., Ting, L.H., and Sawicki, G.S. (2023). Exoskeletons need to react faster than physiological responses to improve standing balance. *Science Robotics*, 8(75), eadf1080.

Boehm, W.L., Nichols, K.M., and Gruben, K.G. (2019). Frequency-dependent contributions of sagittal-plane foot force to upright human standing. *J. Biomech.*, 83, 305–309.

Chen, S., Stevenson, D.T., Yu, S., Mioskowska, M., Yi, J., Su, H., and Trkov, M. (2021). Wearable Knee Assistive Devices for Kneeling Tasks in Construction. *IEEE/ASME Trans. Mechatronics*, 26(4), 1989–1996.

Cleworth, T.W., Horslen, B.C., and Carpenter, M.G. (2012). Influence of real and virtual heights on standing balance. *Gait & posture*, 36(2), 172–176.

Delp, S.L., Anderson, F.C., Arnold, A.S., Loan, P., Habib, A., John, C.T., Guendelman, E., and Thelen, D.G. (2007). Opensim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans. Biomed. Eng.*, 54(11), 1940–1950.

Huang, T.H., Zhang, S., Yu, S., LacLean, M.K., Zhu, J., Di Lallo, A., Jiao, C., Bulea, T.C., Zheng, M., and Su, H. (2022). Modeling and stiffness-based continuous torque control of lightweight quasi-direct-drive knee exoskeletons for versatile walking assistance. *IEEE Trans. Robotics*, 38(3), 1442–1459.

Latash, M.L. and Zatsiorsky, V.M. (1993). Joint stiffness: Myth or reality? *Human Movement Sci.*, 12(6), 653–692.

Nalam, V., Adjei, E., and Lee, H. (2020). Quantification and modeling of ankle stiffness during standing balance. *IEEE Trans. Biomed. Eng.*, 68(6), 1828–1837.

Pfeifer, S., Vallery, H., Hardegger, M., Riener, R., and Perreault, E.J. (2012). Model-based estimation of knee stiffness. *IEEE Trans. Biomed. Eng.*, 59(9), 2604–2612.

Sreenivasan, G., Zhu, C., and Yi, J. (2023). Neural balance control of human quiet stance for construction workers. In *Proc. IEEE Conf. Automat. Sci. Eng.* IEEE. In press.

Zhu, C., Han, F., and Yi, J. (2022). Wearable sensing and knee exoskeleton control for awkward gaits assistance. In *Proc. IEEE Conf. Automat. Sci. Eng.*, 2393–2398. IEEE.

Zhu, C. and Yi, J. (2023). Knee Exoskeleton-Enabled Balance Control of Human Walking Gait with Novel Foot Slip. *IEEE Robot. Automat. Lett.* In press.