A Task-Agnostic Knee Exoskeleton for Reducing Osteoarthritis Pain Across Activities of Daily Life: A Pilot Study

Nikhil V. Divekar*, Ernesto Hernandez Hinojosa*, Jiefu Zhang, and Robert D. Gregg

***Abstract*— Patellofemoral osteoarthritis is a prevalent musculoskeletal disorder characterized by knee pain during physically demanding activities like stair climbing and sit-to-stand transitions. These movements require high knee extension torques, leading to increased quadriceps activation and patellofemoral joint compression, which aggravates pain. While external torque assistance at the knee joint could theoretically reduce joint loads, traditional exoskeletons have not proven effective in managing osteoarthritis due to their rigid actuation, cumbersome attachments, and inadequate control systems. We address these limitations by modifying a commercial post-operative knee brace with a highly-backdrivable actuator and adapting a task-agnostic torque-assist controller, originally designed for lifting and carrying tasks, to accommodate osteoarthritis patients. In pilot trials with four participants with patellofemoral osteoarthritis, our device facilitated substantial reductions in both pain and perceived difficulty across daily activities including stair/ramp navigation, walking, and sit-to-stand transitions. Across all participants and tasks, pain and difficulty were reduced by 0.82 and 0.57 points, respectively (on a scale of 0 to 4). Electromyography revealed decreased quadriceps activation, varying by participant and task. These preliminary findings motivate future research on backdrivable knee exoskeletons as a novel conservative treatment for patellofemoral osteoarthritis.**

I. Introduction

Knee osteoarthritis (OA) is a highly prevalent musculoskeletal disorder affecting ∼14% of American adults [1]. OA can afflict one or more of the three knee joint compartments (medial, lateral, and patellofemoral), with over 24% of knee OA cases being isolated patellofemoral and 40-59% being multi-compartmental [2]–[4]. Physical therapies focus on strengthening the quadriceps to address knee instability and muscle force imbalances between the medial and lateral quadriceps heads [5], [6]. However, pain often limits patients to low joint torque activities like walking, causing them to avoid more demanding tasks such as stair climbing. This restricts general mobility and perpetuates a negative cycle of inactivity, muscle weakness, and OA progression [7].

Conventional unloader knee braces help realign tibiofemoral joint spaces by balancing force distribution between medial and lateral sides. While this alleviates pain in these compartments, these braces cannot address pain from quadriceps muscle action. This muscle action increases compressive forces primarily at the patellofemoral joint [8], [9]. Patellofemoral pain therefore intensifies during activities like stair/ramp climbing and sit-stand [10], which require high knee extension torques and thereby high quadriceps forces. This source of pain inspired the recent design of tri-compartmental unloading knee braces that use springs to help reduce forces and torques in the knee [11]. However, these devices cannot add or remove net energy during human locomotion, making them inadequate for challenging daily activities like climbing up or down stairs [12]. Moreover, the spring can cause a hindrance during swing knee flexion. These limitations highlight the need for a new class of *powered* knee unloaders that can provide a small fraction of biological torque to reduce patellar and quadriceps tendon forces across various activities of daily living (ADLs).

Recent attempts at using knee exoskeletons to relieve pain and increase physical performance in OA patients have shown promise but still face significant challenges. Both the Keeogo and ROAM Ascend exoskeletons require large backpacks and have usability issues related to comfort, weight, and noise [13], [14]. The pneumatically powered Ascend [14] is bulky and, similar to spring-based knee unloaders, does not support knee flexion during late stance and early swing. Moreover, the highly-geared Keeogo [13] was unable to induce acute benefits for knee osteoarthritis patients, likely due to the lengthy user adaptation needed for the task recognition-based controller.

We previously developed a task-agnostic knee exoskeleton to support the quadriceps during lifting-lowering and multi-terrain carrying tasks [15]. This design integrates a backdrivable, quasi-direct drive actuator with a post-operative knee brace, providing high control bandwidth, precise current-based torque control, energy regeneration, quiet operation, and impact compliance [16]–[19]. The exoskeleton features a task-agnostic controller that automatically modulates virtual springs, dampers, and gravity and inertia compensation to assist various activities. Unlike end-to-end neural networks, our controller uses predictable, bounded components with interpretable parameters that can be optimized for biomimetic assistance and fine-tuned for specific applications like OA. This approach also enables seamless task transitions while maintaining natural movement patterns. The exoskeleton reduced quadriceps effort in unimpaired individuals across six key activities: level walking, ramp and stair ascent/descent, and lifting-lowering tasks. These results suggest this technology could similarly reduce quadriceps-induced loads on the patellofemoral compartment to relieve knee OA pain.

This paper presents the deployment and pilot evaluation of our task-agnostic knee exoskeleton for relieving knee

This work was supported by the National Institute of Biomedical Imaging and Bioengineering of the NIH under Award Number R01EB031166. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH.

The authors are with the Department of Robotics, University of Michigan, Ann Arbor, MI 48109, USA. *Authors contributed equally. Contact: {ndivekar, ehdz, zjiefu, rdgregg}@umich.edu

OA pain across the primary activities of daily life. Firstly, we refined our prior controller [15] to support sit-stand transitions rather than lifting-lowering tasks. Secondly, we simplified the brace setup used in [15] by removing the medial thigh plate to prevent unwanted knee forces from strap tightening. Finally, we evaluated the exoskeleton's effectiveness in reducing pain and difficulty across various activities in four participants with patellofemoral-dominant knee OA. Results showed *acute* reductions in both perceived pain and task difficulty, along with participant- and task-dependent reductions in peak and mean quadriceps activation. By providing targeted, backdrivable assistance when needed, this exoskeleton represents a potentially significant advance in non-invasive knee OA management, with implications for improving mobility and patient quality of life.

II. Methods

A. Controller Modifications

Fig. 1 shows a high-level summary of the task-agnostic bilateral knee controller, which was originally developed for lifting-lowering and multi-terrain carrying in [15] and adapted here for supporting knee OA participants. Briefly, the controller consists of core torque bases that are heuristically modified to form task-specific stance torque bases and general (task-invariant) swing torque bases. Next, for stance, task sensitization or multiplication with functions sensitive to certain task characteristics (such as terrain slope) provide task-adaptive stance torque functions. Last, taking the convex sum of the stance and swing torque bases based on the ground reaction force (GRF) unifies them into the final task-adaptive knee torque function.

Here, the "lifting-lowering spring", which was designed to generally support symmetric closed chain squat-like motions, was modified to support sit-stand transitions ("Sit-Stand spring" in Fig. 1). Based on user feedback, the modification essentially involved suppressing the spring torque more for small knee flexion angles. Furthermore, compared to [15], we have an additional basis function for assisting leg clearance ("Swing boost" in Fig. 1). This function supplements the gravity compensation basis by applying knee flexion torques based on the sagittal thigh angle (a commonly used signal for phase-based controllers [20]).

B. Hardware Implementation

The controller was implemented on modified bilateral knee modules of the modular lower-limb exoskeleton system M-BLUE [15], [19]—see Fig. 2. Briefly, this bilateral exoskeleton configuration uses two highly-backdrivable commercial actuators (T-Motor AK80-9, DEPHY driver), each comprising a high-torque pancake motor and an internal 9:1 planetary gearset resulting in a very low reflected friction and inertia (92.1 kg·cm^2). We bypassed the motor driver's default thermal limits and implemented a thermal model-based torque limiter [21], allowing short (1-2 s) bursts of higher peak torques (limited to 25 Nm). We also implemented a ground reaction force sensor (IEE Sense) based on a matrix of force sensitive resistors. An inertial measurement unit (3DM-GX5

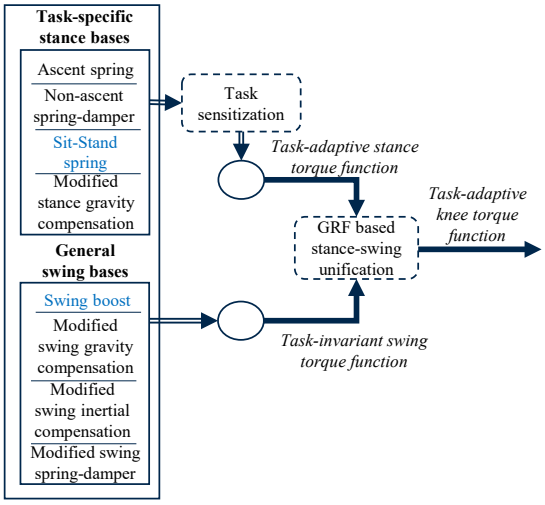

Fig. 1. High-level summary of the task-adaptive knee controller—adapted from [15]. Basis functions that were added or modified are shown in blue.

Fig. 2. Modified bilateral knee exoskeleton for knee OA users.

AHRS, Microstrain) is directly attached to each leg segment (four total) to measure the orientation and angular velocity of both thighs and shanks. The controller for each leg runs on a single board computer (Raspberry Pi 5 8GB, Raspberry Pi Foundation) at 300 Hz with wireless communication to share sensor feedback between legs. The system is powered by two 24 V, 2 Ah powertool battery (Kobalt 24-V Lithium Battery, Kobalt). The total mass of the system is 4.6 kg.

Each actuator is mounted on an off-the-shelf knee brace (T Scope Knee, Breg). We modified the brace setup used in [15] to better suit knee OA participants. Essentially, we removed the medial thigh beam of the brace to allow tightening of the thigh and shank straps with minimal stress on the knee joint in the frontal plane. While this modification makes torque transfer to the human slightly less efficient, it greatly improved comfort of our participants. For user safety, a remote emergency stop switch was implemented to cut off battery power to the motor.

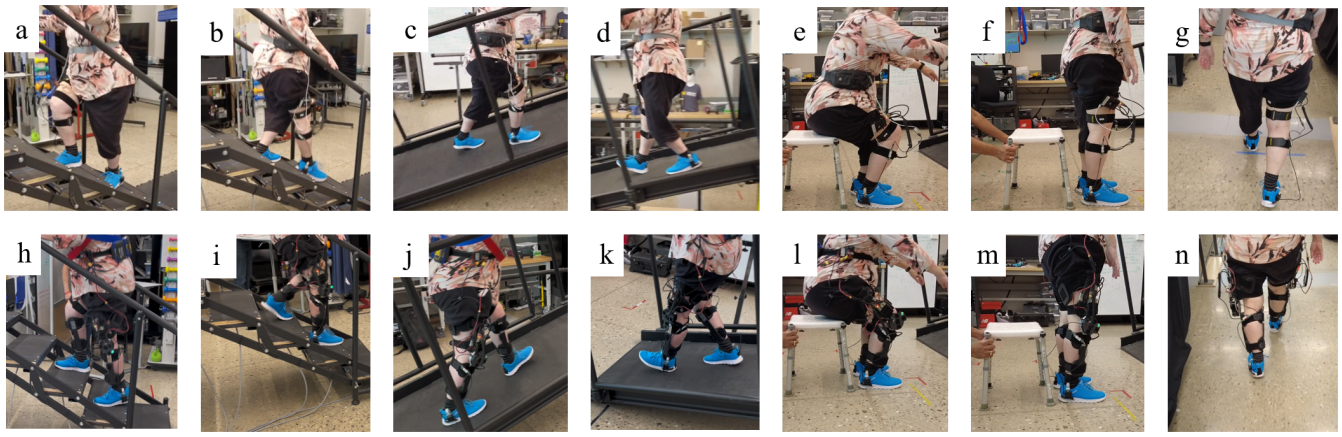

Fig. 3. Participant performing the seven different tasks with both conditions: (a-g) depict the participant without exoskeleton assistance (Bare condition), while (h-m) show the participant performing the same tasks with exoskeleton assistance (Exo condition). The tasks include: (a, h) stair ascent, (b, i) stair descent, (c, j) ramp ascent, (d, k) ramp descent, (e, l) sit-to-stand descent, (f, m) sit-to-stand ascent, and (g, n) level walking.

C. Experimental Design

TABLE I
SUBJECT INFORMATION

	Sex	Age	Weight (kg)	Height (m)
Subj. 1	F	70	94	1.6
Subj. 2	M	81	83	1.83
Subj. 3	F	65	73	1.57
Subj. 4	F	53	52	1.63

The study was approved by the University of Michigan's Institutional Review Board (HUM00201957). We enrolled four participants with pre-eminent pain at the patellofemoral joint—assessed via a questionnaire, sometimes including their x-ray reports. Participants were selected based on self-reported regular pain during walking, which worsened during stair climbing, ensuring they met the study's criteria for patellofemoral OA-related symptoms. The participant information is provided in Table I. All participants gave written consent before participating.

The study involved assessing the effect of our controller/exoskeleton on pain, difficulty, and quadriceps activation levels in a multi-activity test. The activities comprised level ground walking (LW), ramp ascent (RA), ramp descent (RD), stairs ascent (SA), stairs descent (SD), sit-to-stand (STS-A), and stand-to-sit (STS-D); performed on a multi-terrain circuit composed of a level 10 m level walkway, a 3.7-m ramp inclined at 15°, a five-step staircase with a 7 inches (18 cm) step height, and a height adjustable stool.

Before the test, participants attended a separate acclimation session lasting approximately 2-3 hours. During this session, they performed different tasks with the exoskeleton under different levels of assistance (LoA), until they were confident with the device. After acclimation we acquired important gait parameters without the exoskeleton for each activity in our multi-terrain circuit (Fig. 3) for the purpose of applying experimental controls. We acquired the maximum knee extension velocity in stance for ascent (ramp and stairs) and sit-stand transitions, resembling the protocol in [15]. Because OA participants exhibit high intra-subject variance in peak knee velocity during descent tasks (ramp and stairs) and level-ground walking, we instead acquired the time to complete these activities—resembling the average speed for each activity. These parameters served as experimental controls for both the Bare and Exo conditions during the subsequent test visit.

The test visit, which lasted approximately 3-4 hours, was conducted in two conditions: no exoskeleton (Bare) and active exoskeleton (Exo), with the order of the conditions alternated between subsequent participants. In the Exo condition, the level of assistance was kept the same for all participants to fully utilize the peak torque of the actuators. Subjects performed each activity multiple times until obtaining at least 10 gait/task cycles with peak velocities/average speeds within $\pm 10\%$ of their baseline values.

D. Data Collection and Analysis

Pain and difficulty were assessed for each activity using a modified Western Ontario and McMaster Universities Arthritis Index (WOMAC) questionnaire [22], in which participants rate their perceived pain and difficulty on a scale of 0-4, corresponding to "None", "Slight", "Moderate", "Very", and "Extremely". Participants completed the questionnaire at the end of each task trial, following all repetitions of a specific task under a given condition (e.g., after all Exo stair climbing repetitions, all Bare ramp descent repetitions, etc.).

Quadriceps effort was assessed using surface electromyography (EMG). After appropriate skin preparation, we taped three wireless electrodes (Delsys, Massachusetts, USA) onto the participant's right lower limb over the vastus medials oblique (VM), vastus lateralis (VL), and rectus femoris (RF) to assess muscle activation. EMG data was parsed into individual task/gait cycles using the knee angle for sit-stand activities and the FSR for gait activities. Each muscle's EMG was demeaned, bandpass filtered (20 - 200 Hz), and smoothed with a moving 125 ms window RMS filter with 50% overlap. EMG was normalized to the maximum muscle activation level observed during the test.

We then calculated the mean and peak muscle activation for each muscle, taking the difference between the Exo and Bare conditions. Specifically, the peak EMG difference for each muscle/activity was calculated by normalizing the peak EMG of each trial in the Exo condition relative to the Bare condition, using the formula

$$\text{Normalized Peak EMG} = \frac{\text{Exo Peak} - \text{Bare Peak}}{\text{Bare Peak}}$$

Finally, per our previous work [15], the three muscles were lumped together using a weighted average based on each muscle's cross-sectional area to acquire the overall quadriceps mean and peak activations for each activity.

III. Results

Participants reported an average pain reduction of 0.82 points across all tasks and conditions when using the exoskeleton (Fig. 4, Table II). Subject 1 reported a single-point reduction in pain for the stairs and ramp tasks. No changes were observed for other tasks. Subject 2 experienced pain reductions across all tasks except LW and STS-A, where pain remained unchanged. Subject 3 noted relief in all tasks except SD in which pain increased by one point. Subject 4 reported no change in SA, SD, and RA, but observed pain reductions in all other tasks, with the largest reduction of 2 points in STS-D.

TABLE II
PAIN DIFFERENCE (EXO MINUS BARE)

	SA	SD	RA	RD	STS-D	STS-A	LW	Avg.
Subj. 1	-1	-1	-1	-2	0	0	0	-0.71
Subj. 2	-1	-1	-1	-2	-1	-2	0	-1.14
Subj. 3	-2	1	-1	-2	-1	0	0	-0.71
Subj. 4	0	0	0	-1	-2	-1	-1	-0.71
Avg.	-1	-0.25	-0.75	-1.75	-1	-0.75	-0.25	-0.82

Task difficulty decreased by an average of 0.57 points with exoskeleton use (Fig. 4, Table III). Subject 1 reported single-point decreases in difficulty for SA, RA, RD, and STS-A, but found STS-D more difficult with a single-point increase. Other tasks remained unchanged. Subject 2 found all tasks easier except level walking, which became slightly more difficult (single-point increase)—notably this participant had the highest reduction in difficulty of 3 points for STS-A. Subject 3 observed the greatest reduction in difficulty for SA of 2 points, followed by single-point reductions for RA and RD. Sit-to-stand and level walking tasks showed no change, while SD became slightly harder with a single-point increase. Subject 4 reported single-point decreases in SA, STS-D, and level, while RD was slightly more difficult (1 point increase).

The ensemble-averaged EMG activity and torque applied by the exoskeleton (normalized to the task cycle percentage) are presented for each of the seven locomotor tasks in Fig. 5. The plots illustrate how muscle activation patterns differ between the Bare (red) and Exo (blue) conditions and highlight the timing and magnitude of exoskeleton assistance torque (black) throughout the task cycle. Table IV presents

TABLE III
DIFFICULTY DIFFERENCE (EXO MINUS BARE)

	SA	SD	RA	RD	STS-D	STS-A	LW	Avg.
Subj. 1	-1	0	-1	-1	1	-1	0	-0.43
Subj. 2	-1	-1	-2	-1	-1	-3	1	-1.14
Subj. 3	-2	1	-1	-1	0	0	0	-0.43
Subj. 4	-1	0	0	1	-1	0	-1	-0.29
Avg.	-1.25	0	-1	-0.5	-0.25	-1	0	-0.57

the mean EMG differences between the Bare and Exo conditions, where negative values indicate reduced muscle activation with the exoskeleton. Subject 1 experienced decreased activation in most tasks (the across task average change was -1.7%), especially in STS-A having the highest change of -6.8%. Subject 2 showed mixed responses, with slight reductions in RA and STS-A, but slight increases in all other tasks—the across task average change was 1.1%. Subject 3 consistently showed reductions, most notably in STS-A, with only level showing an increase—the across task average change was -3.1%. In contrast, Subject 4 exhibited increased activation across all tasks (3.9% change on average). Overall, the data suggests that the exoskeleton may provide benefits in reducing the mean activation during activities that involve greater muscle exertion, like sit-to-stand transitions with an average reduction of -3.1% across all participants.

TABLE IV
MEAN EMG DIFFERENCE (% CHANGE RELATIVE TO BARE)

	SA	SD	RA	RD	STS-D	STS-A	LW	Avg.
Subj. 1	**-3.2**	**-0.4**	**-0.8**	0.2	**-3.4**	**-6.8**	2.4	**-1.7**
Subj. 2	3.7	1.3	**-2.4**	**-0.8**	3.9	**-1.4**	3.2	1.1
Subj. 3	0.3	**-0.8**	**-1.4**	**-1.7**	**-1.2**	**-5.2**	3.2	**-1**
Subj. 4	0.9	3.4	7.2	2.5	1.2	1.1	11.1	3.9
Avg.	0.4	0.9	0.7	0.0	0.1	**-3.1**	5.0	0.6

Table V highlights changes in peak EMG activation. Subject 1 exhibited the highest peak EMG change of -13.8% observed in STS-A—the across task average change was -2.2%. Subject 2 exhibited peak EMG increase in all tasks except STS-A—the across task average change was 2.2%. Subject 3 exhibited peak EMG reductions in all tasks except level—the across task average change was -3.3%. Subject 4 exhibited peak EMG reductions in SA and STS-A, but increases in all other tasks—the across task average change was was 5.5%. Overall, there were peak EMG reductions for SA, RD, and STS-A. Notably, STS-A had the highest and most consistent change with -8.5%.

TABLE V
PEAK EMG DIFFERENCE (% CHANGE RELATIVE TO BARE).

	SA	SD	RA	RD	STS-D	STS-A	LW	Avg.
Subj. 1	**-9.8**	0.6	1.4	**-3.6**	3.5	**-13.8**	6.1	**-2.2**
Subj. 2	6.5	0.8	0.6	0.8	2.0	**-0.8**	5.7	2.2
Subj. 3	**-5.5**	**-5.3**	**-0.4**	**-2.3**	**-0.3**	**-10.3**	1.2	**-3.3**
Subj. 4	**-0.9**	5.4	14.5	1.2	15.6	**-9.0**	11.5	5.5
Avg.	**-2.4**	0.4	4.0	**-1.0**	5.2	**-8.5**	6.1	0.5

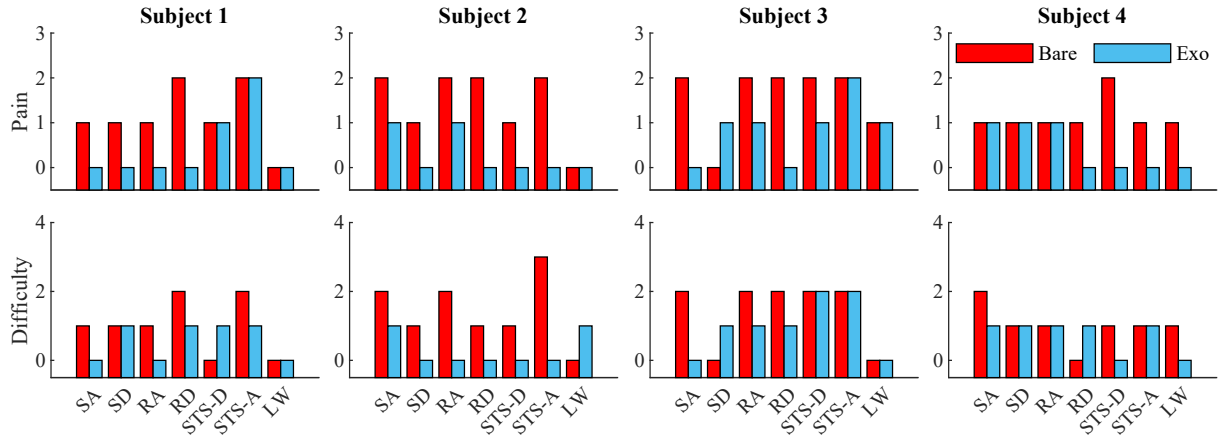

Fig. 4. Perceived pain and difficulty scores during tasks with and without the exoskeleton. The top row illustrates the perceived pain scores reported by the four participants across the seven locomotor tasks: stair ascent (SA), stair descent (SD), ramp ascent (RA), ramp descent (RD), sit-to-stand descent (STS-D), sit-to-stand ascent (STS-A), and level walking (LW). Each bar compares the Bare condition (red bars) with the Exo condition (blue bars). The bottom row displays the corresponding perceived difficulty scores for the same participants and tasks, with the same comparison between the Bare and exoskeleton conditions. The data highlight individual variability in the reported pain and difficulty changes, showcasing task-specific and participant-specific responses to exoskeleton assistance.

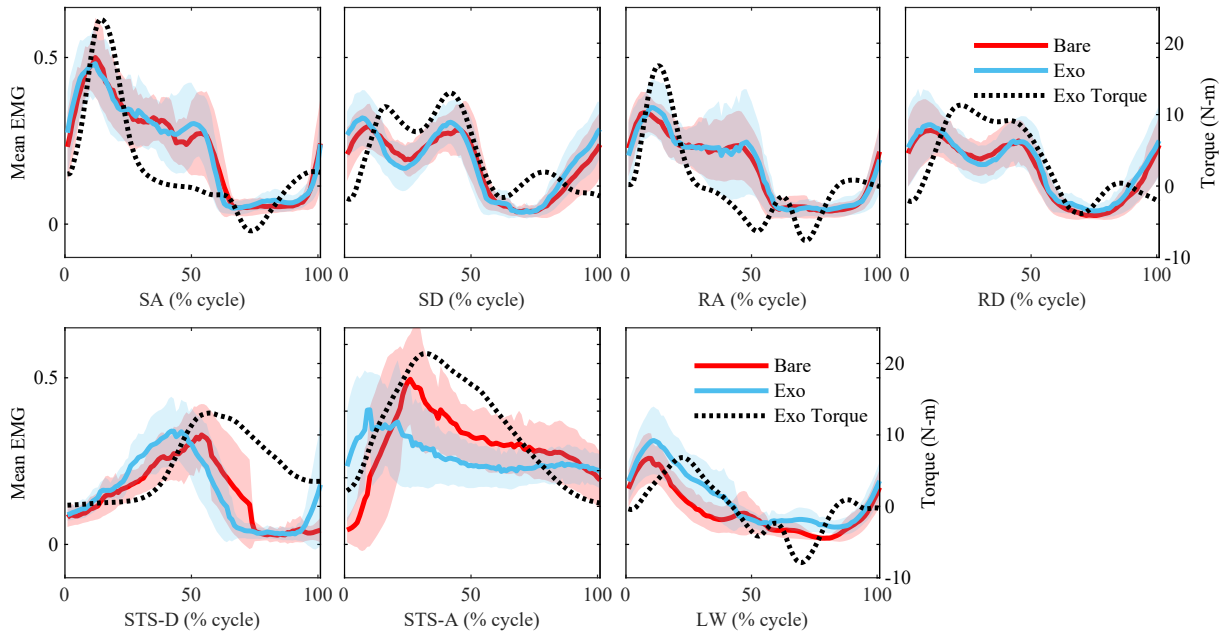

Fig. 5. Mean EMG activation and exoskeleton torque during task cycles. Each plot represents one of the seven locomotor tasks: stair ascent (SA), stair descent (SD), ramp ascent (RA), ramp descent (RD), sit-to-stand descent (STS-D), sit-to-stand ascent (STS-A), and level walking (LW). The red curve shows the mean EMG activation during the Bare condition, while the blue curve shows the mean EMG activation during the exoskeleton-assisted condition. Overlaid on each plot is the mean torque applied by the exoskeleton (black curve), illustrating the relationship between exoskeleton assistance and muscle activation throughout the task cycle.

IV. Discussion

Our study's key finding was that our knee exoskeleton provided *acute* benefits for predominantly patellofemoral OA participants, consistently lowering both their pain levels and the difficulty they experienced during various activities. Traditional unloader knee braces aim to reduce joint loading, but fall short in addressing pain caused by quadriceps muscle action, a limitation that our device directly targets. Unlike spring-based braces, which cannot adjust output torque based on kinematics and ground reaction forces, our system dynamically modulates assistance to inject energy when needed. This is achieved with backdrivable actuators and an intuitive controller that modulates virtual springs, dampers, and gravity-inertia compensation across a range of tasks. This adjustability simplifies tuning and enhances end-user adoption, offering a versatile and practical solution for knee assistance. Moreover, this study addresses the shortcomings of other knee exoskeletons, such as Keeogo and ROAM Ascend. While Keeogo can benefit individuals with knee OA after prolonged use, it has not provided acute benefits, likely due to its highly geared actuators and task-specific controller.

A. Pain and Difficulty Reductions

The most substantial pain reduction was observed during RD, with an average decrease of 1.75 points across participants. This may be attributed to the exoskeleton's capacity to assist the knee in decelerating the body's center of mass, thereby reducing the demand on the quadriceps [23]. In contrast, level walking showed minimal pain reduction, likely due to the lower baseline pain levels typically associated with this activity and its reduced reliance on quadriceps engagement. Unexpectedly, Subject 2 reported increased pain during stair descent. We attribute this to extended loading phases that arise due to hesitancy in utilizing exoskeleton assistance on the riskiest task.

The perceived difficulty of tasks generally correlated with pain levels, although exceptions were observed. For instance, Subject 1 experienced no change in pain during STS-D yet reported an increase in difficulty, suggesting that non-pain-related factors, such as balance or coordination, may have influenced their perception. Similarly, Subject 4 perceived a reduction in pain during RD but noted an increased difficulty, further emphasizing the multifaceted nature of these metrics.

B. Muscle Activity Trends

Muscle activation data revealed notable trends, particularly for STS-A, which exhibited the most pronounced reductions in both mean and peak EMG levels across participants. This aligns with expectations, as the task involves high joint loading and a large range of motion, making it particularly amenable to the exoskeleton's assistive torque. Subjects 1 and 3 showed substantial reductions in peak quadriceps activation during STS-A, SA, and RD, reflecting effective exoskeleton support in mitigating muscular demand. Conversely, Subjects 2 and 4 exhibited less consistent EMG reductions, potentially due to individual differences in balance, motor coordination, or limited acclimatization to the device. These results contrast with our earlier findings in younger, unimpaired users [15], where we observed more consistent reductions in muscle effort. This disparity may indicate that OA participants optimize additional factors, including pain, that influence muscle activation patterns, or they may simply require more acclimation time because older age slows motor adaptation to exoskeletons [24]. Previous work suggests that extended training periods may improve device integration and motor adaptation, thereby enhancing efficacy [25].

An intriguing observation is that pain reduction occurred in some cases despite increases in muscle activation. This challenges the hypothesis that higher quadriceps EMG levels directly correlate with increased joint forces and exacerbated patellofemoral pain. Some studies investigating the neural adaptations with exoskeletons [26], suggest that increased activation may reflect altered muscle recruitment patterns rather than increased joint loading. Future work should further explore the mechanisms underlying pain relief and the complex relationship between muscle activation and joint forces in patients with knee OA.

C. Study Limitations and Future Work

Several limitations of this study warrant discussion. First, the exoskeleton's maximum assistive torque was capped at 25 Nm due to motor constraints, which may have limited its effectiveness for users requiring greater support. This may have been exacerbated by removing the medial thigh plate from the exoskeleton in [15] (to prevent a structural moment in the frontal plane), which may have reduced the effective transmission of assistive torque to the user. Second, task-specific constraints on peak knee extension velocity, particularly during SA, RA, and STS movements, may have introduced variability in kinematic patterns, complicating EMG comparisons across conditions. Developing more precise gait kinematic constraints could improve alignment of muscle activation patterns in future studies, particularly for level walking and descent tasks. Lastly, the potential influence of muscle co-contraction on EMG data should be considered. Co-contraction may have contributed to apparent increases in muscle activation, particularly in tasks requiring stabilization or balance. Incorporating antagonist muscle activation measurements in future analyses could provide a more comprehensive understanding of the exoskeleton's impact on joint loading and pain perception. Future research should focus on addressing the aforementioned limitations while investigating long-term effects, acclimatization processes, and optimization of control strategies for broader clinical and biomechanical applications. Furthermore, future studies should involve larger, more diverse populations to increase the statistical power of these findings.

V. Conclusion

This study provides compelling evidence that backdrivable knee exoskeletons can provide acute reductions in pain and difficulty during a range of locomotor tasks. By addressing several critical limitations of conventional and modern knee-assistive devices, our approach offers new insights into improving knee function and alleviating discomfort. While we cannot definitively link reduced muscle activation to decreased pain, results show the exoskeleton helps users perform previously challenging tasks more comfortably. For example, this relief may enable individuals with OA to engage in physical activities that would otherwise be too painful, fostering muscle strength and potentially slowing the progression of OA. As such, the exoskeleton represents a promising alternative treatment for knee OA. By offering targeted assistance when needed, backdrivable exoskeletons may offer a significant advancement in the non-invasive management of knee OA, with the potential to improve mobility and enhance the quality of life for patients. Further research with larger sample sizes is needed to validate these findings.

References

[1] L. Murphy, T. A. Schwartz, C. G. Helmick, J. B. Renner, G. Tudor, G. Koch, A. Dragomir, W. D. Kalsbeek, G. Luta, and J. M. Jordan, "Lifetime risk of symptomatic knee osteoarthritis," *Arthritis Care & Research*, vol. 59, no. 9, pp. 1207–1213, 2008.

[2] R. Duncan, G. Peat, E. Thomas, L. Wood, E. Hay, and P. Croft, "Does isolated patellofemoral osteoarthritis matter?" *Osteoarthritis and Cartilage*, vol. 17, no. 9, pp. 1151–1155, Sep. 2009.

[3] R. C. Duncan, E. M. Hay, J. Saklatvala, and P. R. Croft, "Prevalence of radiographic osteoarthritis—it all depends on your point of view," *Rheumatology*, vol. 45, no. 6, pp. 757–760, Jun. 2006.

[4] R. D. Heekin and A. A. Fokin, "Incidence of Bicompartmental Osteoarthritis in Patients Undergoing Total and Unicompartmental Knee Arthroplasty: Is the Time Ripe for a Less Radical Treatment?" *The Journal of Knee Surgery*, vol. 27, pp. 77–82, Jul. 2013.

[5] S. C. O'Reilly, A. Jones, K. R. Muir, and M. Doherty, "Quadriceps weakness in knee osteoarthritis: the effect on pain and disability," *Annals of the Rheumatic Diseases*, vol. 57, no. 10, pp. 588–594, Oct. 1998.

[6] S. Amin, K. Baker, J. Niu, M. Clancy, J. Goggins, A. Guermazi, M. Grigoryan, D. J. Hunter, and D. T. Felson, "Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis," *Arthritis & Rheumatism*, vol. 60, no. 1, pp. 189–198, 2009.

[7] J. Dekker, P. Tola, G. Aufdemkampe, and M. Winckers, "Negative affect, pain and disability in osteoarthritis patients: the mediating role of muscle weakness," *Behaviour Research and Therapy*, vol. 31, no. 2, pp. 203–206, Feb. 1993.

[8] J. Heino Brechter and C. M. Powers, "Patellofemoral stress during walking in persons with and without patellofemoral pain," *Medicine and science in sports and exercise*, vol. 34, no. 10, pp. 1582–1593, Oct. 2002.

[9] G. B. Salsich, J. H. Brechter, D. Farwell, and C. M. Powers, "The Effects of Patellar Taping on Knee Kinetics, Kinematics, and Vastus Lateralis Muscle Activity During Stair Ambulation in Individuals With Patellofemoral Pain," *Journal of Orthopaedic & Sports Physical Therapy*, vol. 32, no. 1, pp. 3–10, Jan. 2002.

[10] A. R. Budarick, B. E. MacKeil, S. Fitzgerald, and C. D. Cowper-Smith, "Design Evaluation of a Novel Multicompartment Unloader Knee Brace," *Journal of Biomechanical Engineering*, vol. 142, no. 014502, Nov. 2019.

[11] C. A. McGibbon, S. Brandon, E. L. Bishop, C. Cowper-Smith, and E. N. Biden, "Biomechanical Study of a Tricompartmental Unloader Brace for Patellofemoral or Multicompartment Knee Osteoarthritis," *Frontiers in Bioengineering and Biotechnology*, vol. 8, Jan. 2021.

[12] N. Fukutani, H. Iijima, T. Aoyama, Y. Yamamoto, M. Hiraoka, K. Miyanobu, M. Jinnouchi, E. Kaneda, T. Tsuboyama, and S. Matsuda, "Knee pain during activities of daily living and its relationship with physical activity in patients with early and severe knee osteoarthritis," *Clinical Rheumatology*, vol. 35, no. 9, pp. 2307–2316, Sep. 2016.

[13] C. McGibbon, A. Sexton, A. Jayaraman, S. Deems-Dluhy, E. Fabara, C. Adans-Dester, P. Bonato, F. Marquis, S. Turmel, and E. Belzile, "Evaluation of a lower-extremity robotic exoskeleton for people with knee osteoarthritis," *Assistive Technology*, vol. 34, no. 5, pp. 543–556, Sep. 2022.

[14] ROAM, "Press," 2024. [Online]. Available: https://www.roamrobotics.com/press

[15] N. V. Divekar, G. C. Thomas, A. R. Yerva, H. B. Frame, and R. D. Gregg, "A versatile knee exoskeleton mitigates quadriceps fatigue in lifting, lowering, and carrying tasks," *Science Robotics*, vol. 9, no. 94, Sep. 2024.

[16] S. Seok, A. Wang, M. Y. Chuah, D. J. Hyun, J. Lee, D. M. Otten, J. H. Lang, and S. Kim, "Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot," *IEEE/ASME Transactions on Mechatronics*, vol. 20, no. 3, pp. 1117–1129, Jun. 2015.

[17] G. Kenneally, A. De, and D. E. Koditschek, "Design Principles for a Family of Direct-Drive Legged Robots," *IEEE Robotics and Automation Letters*, vol. 1, no. 2, pp. 900–907, Jul. 2016.

[18] H. Zhu, C. Nesler, N. Divekar, V. Peddinti, and R. D. Gregg, "Design principles for compact, backdrivable actuation in partial-assist powered knee orthoses," *IEEE/ASME Transactions On Mechatronics*, vol. 26, no. 6, pp. 3104–3115, 2021.

[19] C. Nesler, G. Thomas, N. Divekar, E. J. Rouse, and R. D. Gregg, "Enhancing voluntary motion with modular, backdrivable, powered hip and knee orthoses," *IEEE robotics and automation letters*, vol. 7, no. 3, pp. 6155–6162, 2022, publisher: IEEE.

[20] S. Rezazadeh, D. Quintero, N. Divekar, E. Reznick, L. Gray, and R. D. Gregg, "A phase variable approach for improved rhythmic and non-rhythmic control of a powered knee-ankle prosthesis," *IEEE Access*, vol. 7, pp. 109 840–109 855, 2019.

[21] J. Lin, G. C. Thomas, N. V. Divekar, V. Peddinti, and R. D. Gregg, "A Modular Framework for Task-Agnostic, Energy Shaping Control of Lower Limb Exoskeletons," *IEEE Transactions on Control Systems Technology*, vol. 32, no. 6, pp. 2359–2375, Nov. 2024.

[22] E. M. K. Roos, L.S Lohmander, "WOMAC Osteoarthritis Index: Reliability, validity, and responsiveness in patients with arthroscopically assessed osteoarthritis," *Scandinavian Journal of Rheumatology*, vol. 28, no. 4, pp. 210–215, Jan. 1999.

[23] X. Hu, N. T. Pickle, A. M. Grabowski, A. K. Silverman, and S. S. Blemker, "Muscle eccentric contractions increase in downhill and high-grade uphill walking," *Frontiers in bioengineering and biotechnology*, vol. 8, 2020.

[24] A. Lakmazaheri, S. Song, B. B. Vuong, B. Biskner, D. M. Kado, and S. H. Collins, "Optimizing exoskeleton assistance to improve walking speed and energy economy for older adults," *Journal of NeuroEngineering and Rehabilitation*, vol. 21, no. 1, p. 1, Jan. 2024.

[25] K. L. Poggensee and S. H. Collins, "How adaptation, training, and customization contribute to benefits from exoskeleton assistance," *Science Robotics*, vol. 6, no. 58, Sep. 2021.

[26] S. Tortora, L. Tonin, S. Sieghartsleitner, R. Ortner, C. Guger, O. Lennon, D. Coyle, E. Menegatti, and A. D. Felice, "Effect of Lower Limb Exoskeleton on the Modulation of Neural Activity and Gait Classification," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 31, pp. 2988–3003, 2023.