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COBOT – ASSISTED REHABILITATION: REDUCING WORK-RELATED MUSCULOSKELETAL DISORDER (WMSD) RISK ON PHYSIOTHERAPISTS

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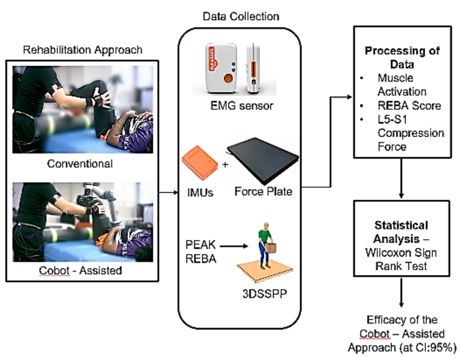
Graphical abstract



Abstract

Recent studies report that 40%–90% of physiotherapists globally experience work-related musculoskeletal disorders (WMSDs) due to repetitive movements and sustained non-neutral postures during manual rehabilitation. This study evaluated the effectiveness of collaborative robots (cobots) in reducing ergonomic risk and WMSD exposure during lower-limb rehabilitation tasks. Seven male participants, acting as simulated physiotherapists, performed passive range-of-motion exercises for the lower extremity with and without cobot assistance. Full-body kinematics were captured using seventeen inertial measurement units, while muscle activity was recorded via surface electromyography. A UR16e cobot supported the patient's limb during rehabilitation, with synchronized biomechanical data acquired from a force plate and motion-tracking system. Ergonomic risk was quantified using the Rapid Entire Body Assessment (REBA), and spinal loading was estimated using the 3D Static Strength Prediction Program. Comparisons between conventional and cobot-assisted conditions were conducted using the Wilcoxon Signed-Rank Test. Cobot assistance reduced left biceps brachii activation during hip abduction–adduction from 63.95 ± 26.10 %MVIC to 6.09 ± 5.13 %MVIC and right erector spinae activation during hip flexion from 54.97 ± 27.82 %MVIC to 8.35 ± 5.03 %MVIC. REBA scores decreased from 8.77 ± 1.50 to 3.68 ± 0.35 during knee flexion–extension, while lumbar compression forces (L5–S1) were reduced from 3276.57 ± 109.90 N to 1176.29 ± 40.87 N. All outcomes showed statistically significant improvements ($p < 0.05$). These findings demonstrate that cobot-assisted rehabilitation substantially reduces muscle load, ergonomic risk, and spinal loading, highlighting its potential to mitigate WMSD risk among physiotherapists.

Keywords: Collaborative Robots, Physiotherapy, Musculoskeletal Disorders, Surface Electromyography, Ergonomic Risks

Abstrak

Kajian terkini menunjukkan bahawa 40% hingga 90% ahli fisioterapi di seluruh dunia mengalami gangguan muskuloskeletal berkaitan kerja (WMSDs) akibat pergerakan berulang dan postur tidak neutral semasa terapi pemulihan manual. Kajian ini menilai keberkesanan robot kolaboratif (cobot) dalam mengurangkan risiko ergonomik dan pendedahan WMSDs semasa pemulihan anggota bawah. Seramai tujuh peserta lelaki, bertindak sebagai ahli fisioterapi simulasi, melaksanakan latihan gerakan pasif (PROM) anggota bawah dengan dan tanpa bantuan cobot. Pergerakan seluruh badan direkodkan menggunakan tujuh belas unit pengukuran inersia (IMU), manakala pengaktifan otot diukur melalui elektrod elektromiografi (EMG). Cobot UR16e digunakan untuk memegang anggota pesakit semasa rehabilitasi, dengan data biomekanik yang disegerakkan diperoleh daripada plat daya dan sistem penjejakan gerakan. Risiko ergonomik dinilai menggunakan Rapid Entire Body Assessment (REBA), manakala beban tulang belakang dianalisis menggunakan perisian 3D Static Strength Prediction Program. Perbandingan antara keadaan konvensional dan berbantukan cobot dianalisis menggunakan Ujian Wilcoxon Signed-Rank. Bantuan cobot mengurangkan pengaktifan otot biseps brakii kiri semasa abduksi dan adduksi pinggul daripada 63.95 ± 26.10 %MVIC kepada 6.09 ± 5.13 %MVIC, serta pengaktifan otot erektor spinae kanan semasa fleksi pinggul daripada 54.97 ± 27.82 %MVIC kepada 8.35 ± 5.03 %MVIC. Skor REBA menurun dengan ketara daripada 8.77 ± 1.50 kepada 3.68 ± 0.35 semasa aktiviti fleksi dan ekstensi lutut. Kekuatan mampatan lumbar (L5-S1) menurun daripada 3276.57 ± 109.90 N kepada 1176.29 ± 40.87 N. Dapatan ini menunjukkan bahawa rehabilitasi berbantukan cobot mengurangkan beban otot, risiko ergonomik dan beban tulang belakang dengan ketara, sekali gus menonjolkan potensinya untuk mengurangkan risiko WMSDs dalam kalangan ahli fisioterapi.

Kata kunci: Robot Kolaboratif, Fisioterapi, Gangguan Muskuloskeletal, Elektromiografi Permukaan, Risiko Ergonomik

1.0 INTRODUCTION

Recent studies from 2019 to 2024 indicate that WMSDs remain highly prevalent among physiotherapists, affecting between 40% and 90% worldwide. This is primarily due to the physically demanding nature of their work, which includes manual therapy, repetitive movements, and awkward postures [1; 2; 3; 4; 5]. These factors make physiotherapists particularly susceptible to WMSDs compared to other profession. For instance, a study by Sagahutu *et al*. in Kigali-Rwanda found that the lower back (L5-S1) was most affected (77.1%) [6]. Another study in India highlighted issues in the lower back, neck, upper back, and shoulder [7].

Collaborative robots (cobots) present a promising solution for reducing WMSDs by performing physically demanding tasks, thereby alleviating the physical strain on physiotherapists [8]. The effectiveness of cobots has been demonstrated in generating precise physiotherapeutic motions, such as proprioceptive neuromuscular facilitation (PNF) movements, which help reduce the workload on physiotherapists [9]. Cobot also facilitate real-time data collection, improving treatment plans through insights into patients' biomechanics [10]. For example, the WALKBOT system improved outcomes in balance and motor recovery for stroke patients compared to conventional therapy [11].

Traditionally, WMSD risks have been evaluated using indirect and qualitative methods, such as ergonomic assessment tools and interviews, which are limited by subjective interpretation. Tools like Rapid Entire Body Assessment (REBA), Rapid Upper Limb Assessment (RULA), and Ovako Working Posture Analysis System (OWAS) focus on body angles and postures that limited by their reliance on subjective nature of self-reported pain [12; 13; 14]. However, advances in wearable sensor technology, such as Inertial Measure Units (IMU) and surface electromyography (sEMG), now allow for direct measurement of motion parameters, joint angles, and muscle activity, enhancing WMSD risk assessments alongside traditional tools [15; 16] .

The surface EMG (sEMG) technology enables precise muscle activity monitoring, and integrating IMU sensors with biomechanical models allows automated ergonomic assessments [17]. Studies show that sEMG and IMU effectively quantify muscle force, fatigue, and involvement in work tasks [18]. However, their application in evaluating ergonomic risks for physiotherapists during rehabilitation remains unexplored. Further research is needed to develop standardized protocols and user-friendly equipment to fully leverage sEMG and IMU benefits in this context.

This research aims to evaluate the efficacy of cobot-assisted rehabilitation in reducing physical strain and improving ergonomic outcomes for physiotherapists. By integrating sEMG and IMU sensors to assess muscle activation and postural risks, alongside static lumbar compression analysis, the study seeks to cover the ergonomic risks during lower limb rehabilitation.

2.0 METHODOLOGY

2.1 Participants

Given the preliminary nature of this pilot study, convenience sampling as a non-probability sampling method was employed to select participants. The risk of WMSDs is similar for both genders, ranging from 55% to 91% in females and 45% to 88% in males [19; 20]. Given this comparable risk profile, this study focuses on male participants, reflecting the demographic composition of the accessible participant pool. A power analysis at a 95% confidence interval (CI) and 80% power confirmed that a sample size of seven physiotherapists was sufficient to detect significant differences in muscle activation, REBA scores, and L5-S1 compression forces. The use of small sample sizes in biomechanics and rehabilitation research is well-documented, with studies successfully obtaining meaningful and statistically significant findings using as few as three participants can yield meaningful and statistically significant findings, achieving accuracies as high as 92.46%[21]. Research in locomotion analysis and biomechanical assessments has demonstrated that methodological approaches can effectively mitigate sample size limitations, ensuring valid and reliable outcomes [22]. Similarly, systematic reviews of robotic rehabilitation have reported that many studies execute on small sample sizes due to feasibility constraints yet still achieve significant results [23]. These findings support the methodological approach of this study, reinforcing the validity of its sample size. In this study, seven male simulated physiotherapists (n = 7; Age: 23.3 ± 1.21 years; Height: 173.9 ± 6.10 cm; Weight: 68.6 ± 11.24 kg) and one simulated patient (n = 1; Age: 26 years; Height: 160 cm; Weight: 61 kg) were recruited. The physiotherapists were trained to execute rehabilitation movements using pre-recorded instructional videos. All participants were verbally briefed on the study protocol and provided written consent. The study followed strict safety measures and was conducted according to guidelines from the Human Research Ethics Committee of Universiti Sains Malaysia (JePem code: 22120825).

2.2 Experimental Setup

The Xsens MVN IMU system (Xsens Technologies BV, Enschede, The Netherlands) was utilized for full-body motion tracking, with seventeen miniature IMUs positioned on the physiotherapists according to placement guidelines provided by Xsens. The sensors were attached with adjustable straps integrated into a suit, as shown in Figure 1a. Participants wore appropriately sized suits to ensure comfort and accurate motion tracking, which was recorded at a sampling frequency of 60 Hz. Muscle activation was recorded using sEMG from iMotions 9.0 (iMotions A/S, Copenhagen, Denmark), with disposable Ag/AgCl electrodes placed on the left and right biceps brachii (LBB, RBB) and erector spinae (LES, RES) following SENIAM guidelines [7]. The skin was cleansed with alcohol wipes before electrode placement [24]. Maximum Voluntary Isometric Contraction (MVIC) was measured for both muscle groups, and the EMG sampling rate was set at 1024 Hz [19; 25].

Figure 1a also illustrates the UR16e collaborative robot (Universal Robots A/S, Odense, Denmark) was fitted with a customized end-effector designed to securely support the patient's limb during rehabilitation exercises. Data exchange between the UR controller and external applications was facilitated via the Real-Time Data Exchange (RTDE) protocol at 125 Hz, following ISO/TS 15066 standards for safe human-machine interaction [26]. A Bertec force plate measured ground reaction forces, as shown in Figure 1b, ensuring precise and safe execution of rehabilitation exercises that closely mimic real-life scenario.

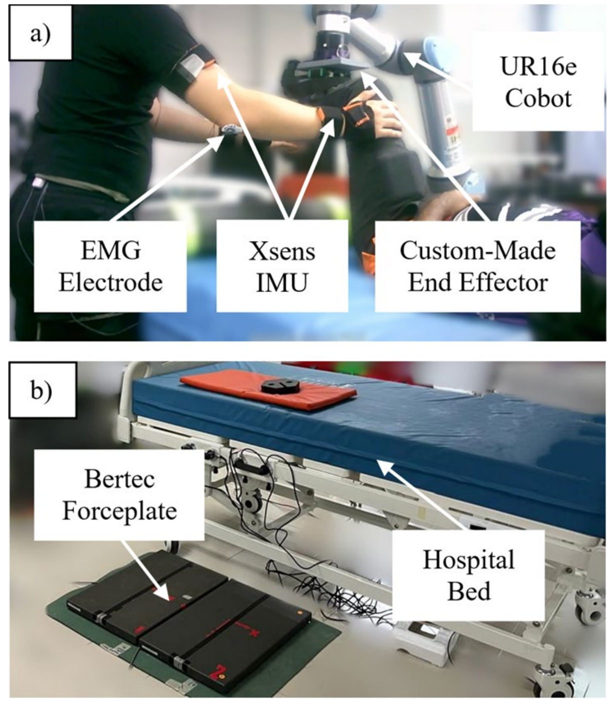


Figure 1(a) Physiotherapist with complete Xsens Awinda suit and iMotions EMG electrode attached during the cobot-assisted rehabilitation exercise using UR16e Cobot and custom-made end effector. (b) Hospital bed layout in conjunction with force plate placement

2.3 Passive Range of Motion (PROM) Rehabilitation Task

The study focused on passive range of motion (PROM) for lower-limb rehabilitation, a common method for aiding stroke patients in restoring function. PROM involves physiotherapists moving a patient's limb through its full range of motion. Table 1 provides descriptions and Xsens avatar images for all PROM tasks. Lower extremities were chosen due to their higher biomechanical load compared to upper extremities. Gait analysis studies have shown that PROM improves the range of motion in the hip, knee, and ankle, which is crucial for restoring lower limb function in post-stroke survivors [27].

Table 1 Summary of the PROM task for lower extremities involved in this study

No	PROM Task	Description
1.	Ankle dorsiflexion and plantar flexion (ADP) 	Ankle dorsiflexion involved lifting the foot towards the shin, while plantar flexion referred to moving it downward. The physiotherapist elevated the patient's limb with their right hand and applied controlled force to the ankle with their left hand.
2.	Hip abduction and adduction (HAA) 	Hip abduction moves the femur laterally, while hip adduction moves it medially. The physiotherapist stabilizes the patient's posture by holding the knee with right hand and the lower leg with the left hand throughout the motion.
3.	Hip flexion (HF) 	Hip flexion involved moving the leg towards the chest with the knee flexed. The physiotherapist supported the knee with their right hand and gently lifted it towards the chest with their left hand.
4.	Knee flexion and extension (KFE) 	Knee flexion involved moving the crus posteriorly relative to the femur around the knee's joint sagittal axis, while knee extension involved moving the crus anteriorly. The physiotherapist stabilized the patient's posture by supporting the thigh with one hand and grasping the crus with the other during the range of motion.

2.4 sEMG Signal Processing

The raw sEMG data was collected from physiotherapists using surface electrodes and processed with iMotion software. EMG signal processing involved two key steps: pre-processing and interpretation. Pre-processing began with a 4th order high pass Butterworth filter at 20 Hz to reduce low-frequency noise and baseline drift. A 50 Hz notch filter was then applied to eliminate power frequency interference. Full-wave rectification was performed to convert negative signal values to positive, facilitating easier analysis and interpretation before MVIC normalization [28].

2.5 Rapid Entire Body Assessment (REBA)

The REBA assessment tool evaluated ergonomic risks to the physiotherapist during PROM tasks. REBA scores were generated from joint angle data in the MVNX file using an automated REBA tool from KAIST's Human Factors and Ergonomics Lab, following standard REBA methods [29]. The required load for REBA calculation was based on the patient's lower limb weight. Bertec force plate data (500 Hz) was synchronized with Xsens postural data (60 Hz) using cubic interpolation in a Python script, providing accurate REBA scores that reflect actual loads and postures at each timestamp.

2.6 Estimation of L5-S1 Compression Force

The compression forces on the physiotherapists' spines were calculated using the 3D Static Strength Prediction Program (3D SSPP), which requires inputs like gender, height, weight, postural angles, and hand loads. Postural angles were derived from Xsens motion capture data, and hand loads were measured with force plates. The posture with the highest REBA score for each task and physiotherapist was used to determine the compression force on the L5-S1 segment, associated with the risk of lower back disorders.

2.7 Statistical Analysis

The Wilcoxon Signed-Rank Test was adopted to compare the efficacy of cobot-assisted against the conventional approach. The Shapiro-Wilk test ($p < 0.05$) confirmed non-normal data distribution on muscle activation, postural angles, and spinal compression forces for both approaches. The Wilcoxon test compared paired samples, ranking absolute differences and summing ranks. A significant difference ($p < 0.05$) at a 95% CI indicates a measurable impact of the cobot-assisted approach on rehabilitation efficacy.

3.0 RESULTS AND DISCUSSION

3.1 Mean Muscle Activation

Figures 2a and 2b compare muscle activation levels during conventional and cobot-assisted rehabilitation. The conventional approach demonstrated high activation of the LBB muscle, measuring 63.95 ± 26.10 %MVIC during the HAA task and 65.21 ± 13.81 %MVIC during the KFE task. Additionally, significant activation of the RBB muscles was observed, peaking at 50.40 ± 27.55 %MVIC during the HAA task and 54.21 ± 18.40 %MVIC during the HF task. Meanwhile, the cobot-assisted approach significantly reduced muscle activation by reducing the LBB activation during HAA and KFE tasks to 6.09 ± 5.13 %MVIC and 7.57 ± 4.23 %MVIC, respectively. With the assistance from cobot, the RBB activation during HAA and HF tasks also decreased to 10.32 ± 11.17 %MVIC and 4.14 ± 4.28 %MVIC, respectively.

Additionally, the erector spinae muscles also showed significant differences when comparing the two rehabilitation approaches. During the HAA and HF tasks in the conventional approach, the LES activation was high at 50.49 ± 22.91 %MVIC and moderate at 39.21 ± 21.46 %MVIC, respectively. The RES activation peaked at 57.25 ± 25.20 %MVIC during the HF task and was moderate at 44.29 ± 26.55 %MVIC during the HAA task. Under cobot-assisted rehabilitation, LES activation during HAA and HF reduced to 6.64 ± 3.67 %MVIC and 7.28 ± 2.91 %MVIC, respectively. The RES activation also showed notable decreases during HF and HAA with reduced variability.

The KFE task recorded the highest muscle activation in the conventional mode, at the LBB with 65.21 ± 13.81 %MVIC, while the ADP task showed the lowest for both biceps brachii and erector spinae. Error bars (95% confidence intervals) indicated less variability with cobot intervention, showing more consistent muscle engagement. The Wilcoxon signed-rank test indicated statistically significant differences ($p < 0.05$) in muscle activation across all PROM exercises, with particularly strong significance ($p = 0.001$) observed during the KFE and HF tasks.

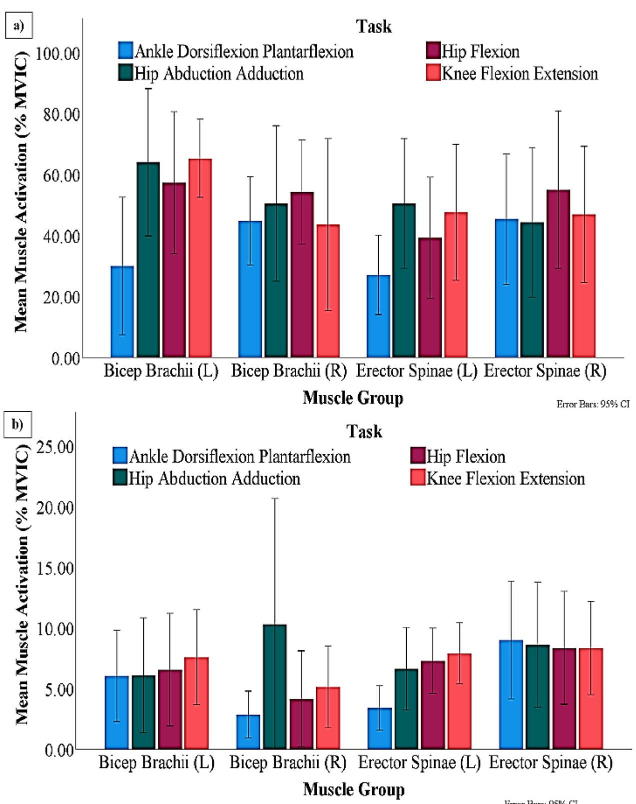


Figure 2 Comparison of mean muscle activation (%MVIC) between (a) conventional and (b) cobot-assisted rehabilitation approaches. Error bars indicate standard deviations at a 95% CI

Based on Figure 2a, it is seen that the conventional approach consistently documented higher muscle activation in the physiotherapists' erector spinae and bicep brachii muscles than the cobot-assisted approach. The LBB activation during HAA task was 63.95 ± 26.10 %MVIC, while the RES activation during HF task was 54.97 ± 27.82 %MVIC. The elevated activity was due to the physiotherapists need to stabilize their trunk and arm while maneuvering the patient's leg [30]. On the contrary, with cobot assistance the RES activation during the HF task declined to 8.35 ± 5.03 %MVIC and the LBB activation during the HAA task plummeted to 6.09 ± 5.13 %MVIC. These findings highlight the cobot's ability to mitigate physiotherapists' muscle strain by minimizing the physical effort required to support and guide the patient's limb. The cobot thus undertakes the majority of the workload, ensuring consistent and stable limb movement.

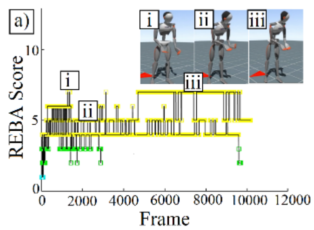
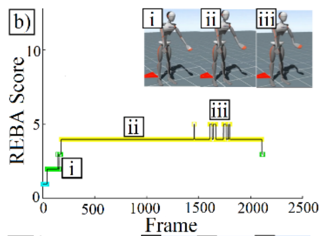
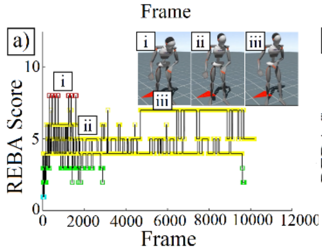
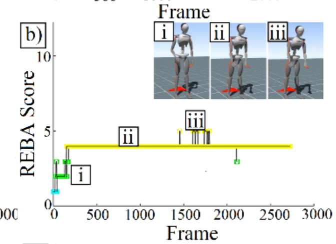
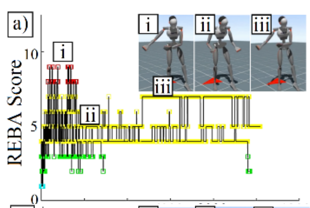
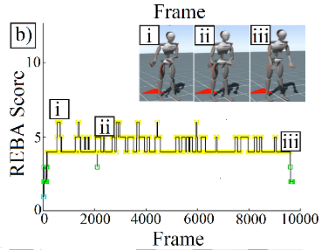
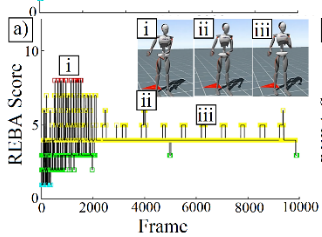
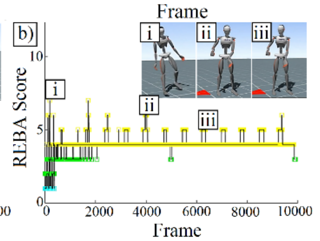
These findings align with existing literature that highlights the benefits of robotic assistance in reducing muscle exertion during rehabilitation tasks. Silvetti *et al*. demonstrated that cobot-assisted manual handling led to a 31.6% reduction in shoulder muscle activation and a 20% reduction in trunk muscle activity compared to manual work, reinforcing the role of cobots in minimizing musculoskeletal stress [31]. Similarly, Caramaschi *et al*. reported that cobot-assisted rehabilitation exercises reduced overall muscle fatigue by 27%, further validating the reducing in physiotherapist muscle strain [32]. These reductions not only prevent early-onset fatigue but also suggest that cobot-supported rehabilitation sessions can be performed for longer durations without increasing the risk of musculoskeletal injuries. Additionally, the narrower confidence intervals observed with cobot intervention suggest that muscle activation remains more consistent and controlled due to the cobot's standardized force assistance. This reduces variability in muscle workload, which is critical in preventing overuse injuries in physiotherapists. Comparable reductions in muscle activation have been observed in exoskeleton-assisted rehabilitation, where Kuschan and Krüger reported EMG reductions of up to 42.38% with a soft robotic exosuit and 35% reductions when using a hybrid robotic-electrical stimulation approach during wrist tasks [33; 34]. The consistent findings across studies highlight the effectiveness of robotic assistance in reducing physical demands on physiotherapists, ultimately improving ergonomic conditions and work sustainability in rehabilitation settings.

3.2 Trend of Continuous REBA Pattern and Mean REBA Score

This section reports the variation in REBA scores and corresponding Xsens avatar postures of the physiotherapist during PROM tasks. Table 2 shows the Xsens avatars and REBA scores for all PROM tasks using both conventional and cobot-assisted methods, with Roman numerals indicating postures related to REBA scoring.

During the conventional ADP task, the REBA score started at 7, decreased to 5 midway, and returned to 7 by the end. In contrast, the cobot-assisted ADP approach started at 2 to 3, maintained around 4, and peaked at 5. For the HAA task, the conventional approach began at 8, fluctuated between 5 and 7, and ended at 7, while the cobot-assisted method showed similar trend as ADP task. The conventional HF task peaked at 9 and ranged from 5 to 7, whereas the cobot-assisted approach started at 6, stabilized around 5 to 6, and ended at 4. In the KFE task, the conventional approach started at 8 and varied between 5 and 7 throughout, while the cobot-assisted approach began at 7, dropped to 5, and ended up with 6. Overall, cobot-assisted methods showed lower REBA scores, indicating reduced ergonomic risk

Table 2 Summary of continuous REBA pattern across all PROM tasks for both approaches

PROM	Conventional Approach	Cobot – Assisted Approach
ADP*		
HAA*		
HF*		
KFE*		

*Abbreviation for each task is as follows, adhering to the Section 2.3: Passive Range of Motion (PROM) Rehabilitation Task

Figure 3 shows the mean REBA scores for various PROM tasks, comparing conventional and cobot-assisted approaches. It is observed that the mean REBA score was successfully decreased by using cobot during the ADP task from 5.10 ± 0.45 to 3.65 ± 0.19. In the HAA task, the score dropped from 7.23 ± 0.56 to 3.75 ± 0.18. The HF and KFE tasks resulted in the highest REBA scores of 8.57 ± 0.74 and 8.77 ± 1.50, respectively with the conventional approach, which decreased to 3.79 ± 0.39 for HF and 3.68 ± 0.35 for KFE with cobot's assistance. Overall, cobot-assisted approach significantly reduced ergonomic risks ($p < 0.05$) across all tasks.

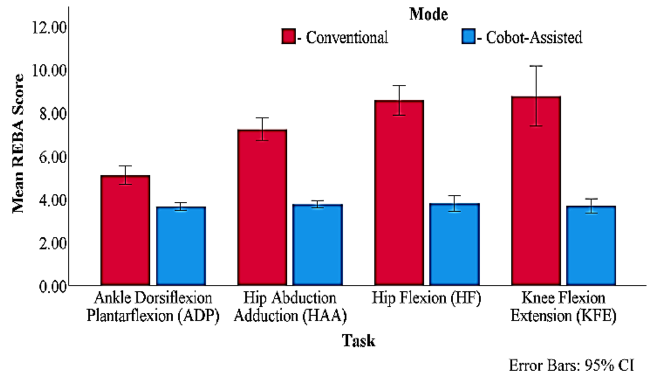


Figure 3 Mean REBA scores across PROM tasks in conventional and cobot-assisted rehabilitation. Error bars indicate standard deviations at 95% CI

According to Figure 3, the high REBA scores of 8.57 ± 0.74 for the HF task and 8.77 ± 1.50 for the KFE task through the conventional approach correspond to the physiotherapist's trunk flexion exceeding the recommended range of 30° [35]. Analysis of IMU data indicated that physiotherapists maintained trunk flexion angles of 37.24° ± 5.57° to 37.24 ± 5.57° and 37.76° ± 4.02° to 37.76 ± 4.02° during these tasks, supporting previous findings that sustained trunk flexion above the recommended ergonomic limit of 30° poses significant ergonomic risks [36]. Additionally, the high REBA score in the HF task was also influenced by right wrist flexion of 45.38 ± 14.28°, surpassing the recommended range of 0° to 10° [37]. Notably, the moderate REBA score of 7.23 ± 0.56 for the HAA task in the conventional approach was mainly caused by excessive neck flexion at 22.76 ± 4.30°, which exceeds the recommended range of 0° to 15° [38]. The REBA tool effectively captures these postural deviations, which result in higher scores and reflect increased physical strain on physiotherapists [39].

In contrast, cobot-assisted rehabilitation significantly reduced REBA scores, with none of the tasks exceeding a score of 4. This substantial decrease in REBA scores highlights the cobot's ability to reduce physical strain on physiotherapists by minimizing the need for excessive trunk flexion, stabilizing wrist positions, and reducing prolonged static loads. The results are consistent with findings in other fields, such as colonoscopy procedures, where ergonomic interventions reduced REBA scores from 11 to 6, and in robot-assisted rehabilitation, where scores dropped from 13 to 5, demonstrating the significant ergonomic benefits of robotic assistance [40; 41]. Further supporting these findings, El Makrini *et al*. examined cobot-assisted human-robot collaboration and found out that cobot integration significantly improved ergonomic postures and lowered REBA scores by reducing awkward trunk movements and optimizing joint angles [42]. This enhancement in postural ergonomics demonstrates how cobot assistance can effectively reduce physiotherapists' exposure to high-risk postures, ultimately decreasing the likelihood of WMSDs and long-term physical strain.

3.3 L5-S1 Compression Force

Figure 4 displays the mean compression force on L5-S1 for each PROM task, alongside the physiotherapist posture model used in the estimation. For the conventional approach, mean forces were recorded around 2463.57 ± 71.46 N for ADP task, 1414.86 ± 121.24 N for HAA task, 2533.43 ± 81.10 N for HF task, and 3276.57 ± 109.90 N for KFE task. In comparison, the utilization of cobot resulted in a substantial decrease in the compression forces, typically not surpassing 1200 N, with a p-value of less than 0.01. The greatest reduction of compression forces from 3276.57 ± 109.90 N to 1176.29 ± 40.87 N was observed during the KFE task. Despite the conventional approach resulted in compression force within the NIOSH safety limit of 3400 N, the cobot-assisted intervention provided a larger safety margin, minimizing the likelihood of lumbar spine injuries over time [43].

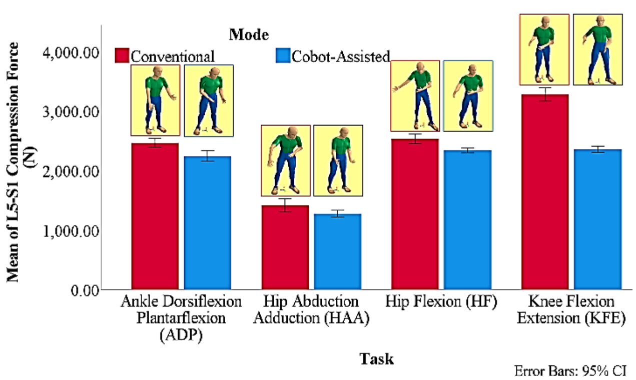


Figure 4 Mean L5-S1 compression forces during PROM tasks in conventional and cobot-assisted rehabilitation approaches. Error bars represent standard deviations at a 95% CI. (Illustrated postures above each bar represent physiotherapist body positions at peak REBA scores for each PROM task)

Referring to Figure 4, the physiotherapists' L5-S1 segment experienced a maximum compression force of 3276.57 ± 3.43 N during KFE tasks using the conventional approach. This large force magnitude implies that the physiotherapist bears a significant workload and bend their torso substantially to complete the activity [44; 45]. For the same task, cobot effectively maintained a mean compression force of the physiotherapists' L5-S1 segment at 1176.29 ± 40.87 N. The reduction suggests that cobot-supported tasks are substantially less likely to contribute to lumbar spine injuries, as the cobot compensates for the lower limb load, redistributing force away from the physiotherapist's spine. This workload redistribution is particularly critical given the high prevalence of lower back disorders among physiotherapists, which often result from prolonged spinal loading and repeated flexion-extension movements [46].

These findings align with Eskandari *et al*., who examined a back-support exoskeleton's effect on spinal loading and reported reduction in peak compression and shear forces by approximately 15%, particularly when physiotherapists engaged in tasks requiring larger trunk flexion angles [47]. Their study further revealed that back muscle activation and corresponding muscle forces were reduced during the lowering phase of lifting tasks, reinforcing the biomechanical advantage of robotic support in alleviating spinal stress. Additionally, study by Koopman *et al*. has shown that, with an active exoskeleton reducing peak spinal compression forces by about 18% during lifting tasks [48]. These results provide strong quantitative evidence supporting the role of cobot-assisted rehabilitation in reducing lower back compression forces, thereby enhancing workplace safety and lowering the risk of lumbar injuries.

3.4 Future Directions and Practical Implications

While this study provides strong preliminary evidence of the benefits of cobot-assisted rehabilitation in reducing muscle activation, ergonomic strain, and spinal compression forces, several potential biases should be acknowledged. One key limitation is the lab-controlled nature of the study, which ensured consistency in measurements but may not fully reflect the dynamic challenges of real-world clinical settings. Physiotherapists typically adjust their posture and movement based on patient needs and workspace constraints, whereas this study restricted movement to a force plate area, potentially overestimating ergonomic risks compared to natural rehabilitation environments. Future research should explore cobot integration in clinical settings to better assess its practical impact. Another consideration is sample demographics, as this study involved a single-gender participant group, which limits its ability to capture gender-based biomechanical differences in muscle activation and spinal loading.

Additionally, factors such as experience level, specialization, and ergonomic habits may influence how physiotherapists interact with cobot assistance. Future studies should include diverse participant pools to enhance generalizability. Although statistical analyses confirmed the adequacy of the sample size for detecting significant differences, a larger multi-center study is recommended to improve external validity and ensure the findings are applicable across different clinical environments and patient populations. Importantly, this study was designed as a cross-sectional pilot study, making it well-suited for assessing the immediate effects of cobot-assisted rehabilitation. However, since WMSDs develop gradually, this study does not account for long-term impacts on physiotherapists' occupational health.

Lastly, longitudinal studies should track whether cobot interventions lead to sustained reductions in physical strain, fatigue, and injury risk over time. Finally, the selected rehabilitation tasks effectively demonstrated cobot benefits but do not represent the full scope of physiotherapy interventions. Expanding future research to include a wider range of rehabilitation tasks will provide a more comprehensive understanding of cobot-assisted workload reduction in physiotherapy practice.

4.0 CONCLUSION

The findings demonstrate that cobot-assisted rehabilitation substantially reduces biomechanical and ergonomic loading during lower-limb physiotherapy tasks. The utilization of the cobot during the HF task resulted in a significant decrease in the activity of the right erector spinae muscle, from 54.97 ± 27.82 %MVIC to 8.35 ± 5.03 %MVIC. Moreover, the employment of cobot in the HAA task resulted in a significant decrease in the activation of the left bicep brachii muscle, from 63.95 ± 26.10 %MVIC to 6.09 ± 5.13 %MVIC. Apart from that, the REBA scores recorded through the HF and KFE tasks significantly decreased from 8.57 ± 0.74 to 3.79 ± 0.39 and from 8.77 ± 1.50 to 3.68 ± 0.36, respectively, when the cobot was employed. Besides, the compression force at the L5-S1 segment decreased from 3276.57 ± 109.90 N to 1176.29 ± 40.87 N when the cobot was used during the KFE task. In short, implementing cobot-assisted rehabilitation in real-world physiotherapy settings could reduce the physical strain associated with heavy loads and repetitive tasks, thereby enhancing physiotherapist well-being and workplace ergonomics.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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