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The Effect of Crutch Gait Pattern on Shoulder Reaction Force when Walking with Lower Limb Exoskeletons

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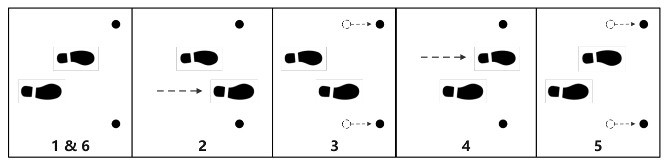
Abstract— Lower limb exoskeleton robots have shown great potential in assistive and rehabilitative applications, allowing individuals with motor impairment, such as spinal cord injury (SCI) patients, to perform overground gait. Most assistive lower limb exoskeletons require users to use crutches to balance themselves during standing and walking. However, long-term crutch usage has been demonstrated to be potentially harmful to the shoulder joints, due to the repetitive high shoulder reaction forces. Investigations into the shoulder loads experienced during exoskeleton use are needed to understand the extent of this harm and, if required, to reduce the risk of injury. In this preliminary study, the effects of different gait patterns on the shoulder load are investigated in an experiment involving three able-bodied individuals. Specifically, the differences in shoulder load during exoskeleton walking are studied with two commonly-observed gait patterns: (1) the four-point parallel crutch gait and (2) the four-point reciprocal crutch gait. Contact forces between the ground and the human-exoskeleton system were recorded and used to indicate shoulder reaction force. The results suggested no significant differences in maximum force and maximum rate of loading between the two crutch gait patterns, and only minor differences in force time integral. This indicates that shoulder reaction force may not be a significant factor when choosing between crutch gaits during exoskeleton use.

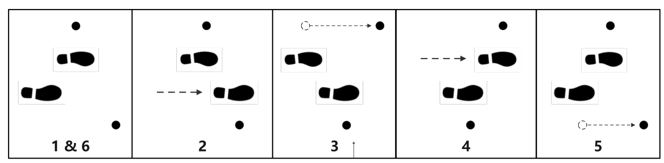
I. INTRODUCTION

Lower limb exoskeleton robots have become a state-of-art technology that shows benefits in assisting people with leg weakness and impairment to rebuild their gait capability [1] and improve confidence and quality of lives [2]. Though some exoskeleton robots can self-balance [3], [4], most assistive lower limb exoskeleton robots require wearers to use crutches, not only for safety reasons but also for operational flexibility (to maintain balance and determine gait heading). However, the literature shows that incorrect crutch usage will lead to shoulder pain, joint degeneration, and even irreversible damages [5]–[7].

Different gait patterns have also been found to produce different biomechanics on the shoulder joint of crutch users [8]. Observations noted in the literature have shown that different people adopt different crutch gait patterns after they are trained to walk in a lower limb exoskeleton robot [9], [10]. The two most common gait patterns are the 4-point parallel crutch gait pattern (Gait-P, shown in Figure 1(a)) and the 4-point reciprocal crutch gait pattern (Gait-R, shown in Figure 1(b)) [9]. To date, these two gaits have not been compared in terms of their performance or effects. The Gait-P was analysed in [9] kinematically, thus did not account for the forces and joint loading, while a kinetic simulation method for analysing the Gait-R has also been developed [11] but not in comparison to Gait-P.



(a) 4-point Parallel Crutch Gait Pattern



(b) 4-point Reciprocal Crutch Gait Pattern

Fig. 1. Different Crutch Gait Patterns

In this work, the shoulder reaction force is studied with respect to the two gait patterns mentioned. This is because shoulder reaction force is widely studied in assistive walking equipment usage [12] and is one of main causes of shoulder injury [13], [14]. The aims of this preliminary study are to improve the understanding of the biomechanics of crtuch-assisted exoskeleton gait, and as such, help reduce the risk of injury from crutch usage.

II. MATERIALS AND METHODS

The experimental setup, protocol, data collection and analysis are presented in this section, with the aim to compare the effect of the two gait patterns on the shoulder joint reaction force.

A. Experimental Platform

1) Lower Limb Exoskeleton Robot: The lower limb exoskeleton robot used in this work is a modified ExoMotus-X2 (Fourier Intelligence Co., Ltd., Shanghai). It has 4 active joints (left leg hip, left leg knee, right leg hip, right leg knee), and fixed ankles during the walking process in this study. A custom application developed using CANOpen Robot Controller (CORC) [15] is implemented on the device, to run a standard walking trajectory (a trajectory used with paraplegic

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users) for all participants. The device is controlled by the user using buttons on the forearm crutch, requiring the user to actively press a trigger under the index finger to initiate and complete each step.

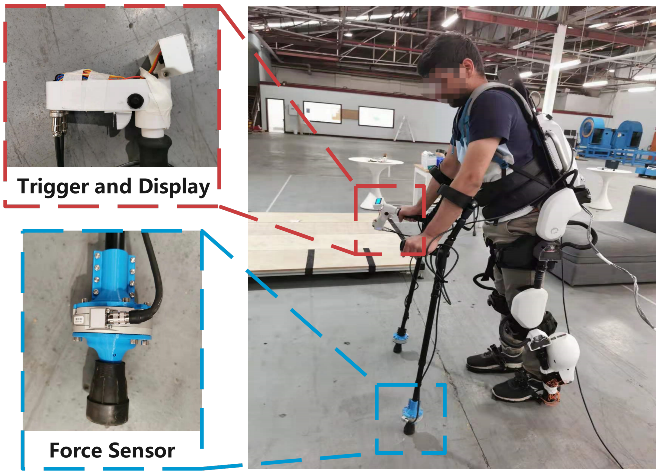

Fig. 2. Experimental Platform

The exoskeleton robot walks one step at a time when the trigger is held down. The state of the trigger and the exoskeleton robot are read by the data collection system and is used to determine when the gait cycle starts at the data analysis stage.

2) Ground Reaction Force Sensors: To measure the force between the ground and the human-exoskeleton system, a pair of forearm crutches are instrumented with Force/Torque (F/T) sensors, shown in Figure 2. T80-6A01-CAN (ROBOTOUS Inc., Korea) F/T sensors were mounted to the base of the crutches, allowing the measurement of 6 degree-of-freedom contact force and torque between the crutch tip and the ground.

B. Experimental Procedure

Three able-bodied participants with no history of neurological disease were recruited for participation with written informed consent. The Human Research Ethics Committee of the University of Melbourne approved the study under Ethics Application ID 20528.

Participants were first instructed on how to operate the exoskeleton. The exoskeleton was then adjusted to ensure joint alignment and the exoskeleton worn by the participant. A familiarisation process was carried out before each formal experiment, allowing participants to get familiar with the trigger usage and the two crutch gait patterns. This process lasted as long as the user needed to feel comfortable.

In the formal experiment, each participant completed six trials — three for each gait pattern. The gait pattern chosen for each trial alternated, with the first gait pattern randomised for each participant. In each trial, participants were asked to walk continuously for 5 metres using the lower limb exoskeleton with the specified crutch gait pattern. The positions of the crutches were monitored to ensure that the crutch pattern was adhered to, but no instruction was given during the trial. In total, each participant completed a minimum of 24 steps with each crutch gait pattern.

C. Data Collection

The following data were recorded at 100Hz sampling rate:

- A Timestamp (t_k)
- The joint angle value of 4 active joints of the lower limb exoskeleton robot. ($\theta(t_k) \in \mathbb{R}^4$)
- The state of the trigger at the crutch ($c(t_k)$) and the control state of the exoskeleton ($s(t_k)$)
- The values from the F/T sensors for the left and right crutches ($[\mathbf{f}_l(t_k), \mathbf{M}_l(t_k)]^T \in [\mathbb{R}^3, \mathbb{R}^3]^T,\ l = L, R$)

D. Data Processing and Analysis

All collected data were processed using Matlab 2019b (Mathworks, USA). The timestamp, exoskeleton joint angle data, the state value of the trigger, and the control state of the exoskeleton were used to identify when the steps begun and stopped. Only the force data from the force sensors ($\mathbf{f}_l$) were used for this analysis.

1) Preprocessing: For each participant ($i = 1, 2, 3$), the data were segmented into each step ($j = 1, ..., M$). Steps in which the user stopped the movement midway through (by releasing the trigger) were discarded. The Euclidean norm of the force sensor data was calculated, to produce an overall force magnitude ($F_k(t_k) \equiv ||\mathbf{f}_l(t_k)||$).

To reduce the effects of noise, data were filtered and fitted using the cubic smoothing spline method *csaps* with the smoothing parameter p set to 0.99999, producing a smooth function approximating the force data for each trial $F_{spline,k,i,j}(t)$. This function was normalised by bodyweight ($F_{norm,k,i,j}(t) = F_{s,k,i,j}(t)/m_i$) for each participant where m_i was the mass of participant i. Finally, the normalised force function of the left and right crutch were relabelled to be either the swing-side crutch ($F_{norm,sw,i,j}(t)$) or the stance-side crutch ($F_{norm,st,i,j}(t)$).

2) Metrics: Three metrics related to the shoulder load are evaluated for each crutch: maximum force, maximum rate of loading (ROL), and force-time integral (FTI). These metrics have been shown to be relevant in shoulder joint force evaluation [12], indicative of both instantaneous events and long term loading conditions which may cause injury. In this work, different from [12], the contact force is normalized by body weight, due to the relationship between absolute shoulder reaction force and body weight [7], and to allow comparisons between participants. The metrics are formally defined as follows:

a) Maximum force: was defined as the highest normalised force occurring during a given step:

$$F_{max} = \max_t F_{norm,m,i,j}(t) \tag{1}$$

b) Maximum ROL: was defined as the highest derivative value of the occurring force during a step:

$$ROL_{max} = \max_t \frac{dF_{norm,m,i,j}(t)}{dt} \tag{2}$$

c) FTI: represents the total amount of force borne by the shoulder during a step:

$$FTI = \int_{t_0}^{t_f} F_{norm,m,i,j}(t)dt \tag{3}$$

3) Comparisons: This work explores the difference in crutch forces between the Gait-P and Gait-R. It is clear that these loading conditions are different between the swing side crutch and the stance side crutch in a given step. As such, comparisons were made for all metrics between the swing side and stance side crutches of the Gait-P and Gait-R using a Wilcoxon Sign-Ranked Test.

III. RESULTS

The calculated means and standard deviations for all calculated metrics are shown in Table I.

A. Maximum Force and Maximum Rate of Loading

No significant difference (p<0.05) was observed between Gait-P and Gait-R in the maximum normalised force or maximum rate of loading, in either the stance crutch or the swing crutch, as seen in Figures 3 and 4.

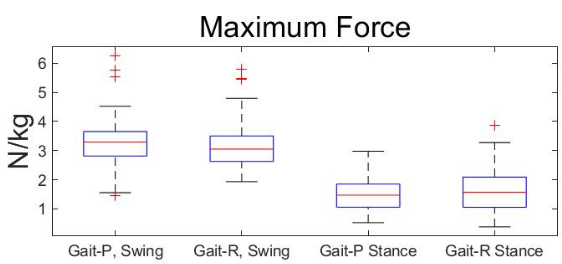

Fig. 3. Maximum Force

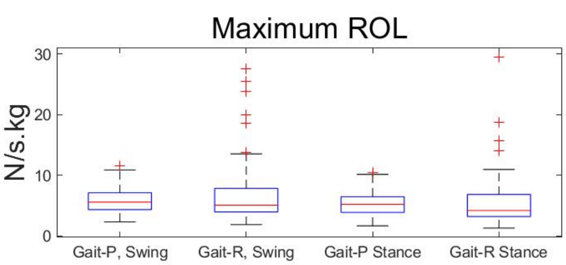

Fig. 4. Maximum Rate of Loading

B. Force Time Integral

A significant difference (p<0.05) was observed between Gait-P and Gait-R in the force time integral, in both the stance crutch or the swing crutch. As can be seen in Figure 5 and Table I, the swing crutch has a higher FTI and stance crutch a lower FTI in Gait-P compared to Gait-R.

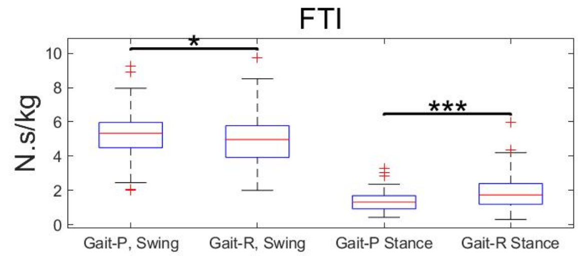

Fig. 5. Force Time Integral of Normalied Crutch Force (*: $p < 0.05$, ***: $p < 0.001$)

IV. DISCUSSION

The results of this work suggest that there are no significant differences in maximum shoulder load or maximum rate of load between the four-point recipricol (Gait-R) and four-point parallel (Gait-P) gaits, and a significant, but small difference in the force time integral. Specifically, measurements of the FTI indicate a higher load in the swing crutch and lower load in the stance crutch during steps taken with Gait-P. However, as steps are rarely taken in isolation and each crutch alternates between stance and swing during continuous gait, it is noted that the difference in FTI for each crutch over a full stride is smaller.

A secondary observation, as can be seen in Figure 4, is that there are more high outliers in the maximum rate of loading, in both the swing and stance crutch. This may be of interest in injury prevention, as injury may occur with only a low number of high rate of loading events. However, these outliers may also be explained by loss of balance (and subsequent correction by the users) and thus their frequency may also be reduced by further training with the exoskeleton.

Nevertheless, these results suggest that shoulder load may be only a minor factor when choosing between crutch gait patterns in exoskeleton use. As such, this choice can be made with other factors in mind, such as user confidence or balance ability. However, it is noted that whilst that the results of this study imply that the difference between the shoulder reaction forces are limited, it does not assess the potential of the observed forces to result in shoulder injury.

A. Limitations

There are a number of limitations associated with this study which may affect the reliability of the results. First, only able-bodied participants were included in this study. It is clear that the movement characteristics of able-bodied individuals are different to those who have mobility impairments. For example, those without lower limb sensation tend to rely more heavily on the use of their crutches due to improved balance perception, thus it is likely that some differences in results would be observed. Secondly, this preliminary study only included three participants. This is clearly a limited number

TABLE I

Calculated Crutch Force Metrics for Gait-P and Gait-R

Metric	Swing Crutch		Stance Crutch	
	Gait-P	Gait-R	Gait-P	Gait-R
F_{max} (N/kg)	3.31 (0.86)	3.17 (0.86)	1.50 (0.55)	1.63 (0.74)
ROL_{max} (N/s.kg)	5.80 (2.07)	6.71 (5.21)	5.23 (1.85)	5.47 (4.27)
FTI (N.s/kg)	5.30 (1.39)	4.99 (1.56)	1.37 (0.47)	1.91 (0.95)

of participants, which is likely to have influenced the evaluation of the significance of the results. Thirdly, this work investigated a single fixed exoskeleton movement trajectory which had been implemented on a single exoskeleton. However, it is possible that a different trajectory may produce different results, or, indeed, that the trajectory may be optimised to reduce shoulder load for a particular crutch gait pattern. Finally, the analysis considers only the magnitude of the ground reaction force as a measure of the shoulder reaction force. Whilst it is clear that the kinematic chain of the crutch, forearm and upper arm links the ground to the shoulder, this analysis does not take into account any change in force as a result of elbow flexion or extension.

V. CONCLUSIONS AND FUTURE WORKS

In this preliminary work, the influence of crutch gait pattern on shoulder reaction force has been investigated between two different gait patterns when walking with a lower limb exoskeleton robot. The study found no major differences across three calculated metrics, suggesting that shoulder reaction force (and possibly risk of shoulder injury) may not be a large factor in deciding which gait to adopt in lower limb exoskeleton use.

Possible avenues of future work may include extending the study to include more participants and participants with mobility impairments; biomechanical analysis to estimate true shoulder reaction force; exploration of adjustment of the exoskeleton movement for different crutch gait patterns; and/or trajectory optimisation techniques to minimise shoulder reaction force.

ACKNOWLEDGMENT

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STATEMENT ON CONFLICT OF INTEREST

The ExoMotus X2 exoskeleton used in this study is a product of Fourier Intelligence, of which one of the authors is an employee.

References

[1] A. J. Young and D. P. Ferris, "State of the art and future directions for lower limb robotic exoskeletons," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 25, no. 2, pp. 171–182, 2016.

[2] S. Zabel, Z. Lockhart, N. Badiani, J. Cornish, L. Falzon, A. Flis, K. Patterson, S. Gregor, and J. Vaughan-Graham, "Physiotherapy students' perspectives on the use and implementation of exoskeletons as a rehabilitative technology in clinical settings," Disability and Rehabilitation: Assistive Technology, pp. 1–8, 2020.

[3] O. Harib, A. Hereid, A. Agrawal, T. Gurriet, S. Finet, G. Boeris, A. Duburcq, M. E. Mungai, M. Masselin, A. D. Ames et al., "Feedback control of an exoskeleton for paraplegics: Toward robustly stable, hands-free dynamic walking," IEEE Control Systems Magazine, vol. 38, no. 6, pp. 61–87, 2018.

[4] G. Barbareschi, R. Richards, M. Thornton, T. Carlson, and C. Holloway, "Statically vs dynamically balanced gait: Analysis of a robotic exoskeleton compared with a human," in 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2015, pp. 6728–6731.

[5] D. Brasil-Barros-da Silva and E. Fachin-Martins, "Pain mapping and health-related conditions in relation to forearm crutch usage: A cross-sectional study," Assistive Technology, pp. 1–7, 2020.

[6] N. B. Jain, L. D. Higgins, J. N. Katz, and E. Garshick, "Association of shoulder pain with the use of mobility devices in persons with chronic spinal cord injury," PM & R, vol. 2, no. 10, pp. 896–900, 2010.

[7] K. Opila, A. Nicol, and J. Paul, "Upper limb loadings of gait with crutches," Journal of Biomechanical Engineering, vol. 109, no. 4, pp. 285–290, 1987.

[8] E. Perez-Rizo, F. Trincado-Alonso, S. Perez-Nombela, A. del Ama-Espinosa, F. Jimenez-Diaz, V. Lozano-Berrio, and A. Gil-Agudo, "Application of a model to analyze shoulder biomechanics in adult patients with spinal cord injury when walking with crutches in two different gait patterns," NeuroRehabilitation, vol. 40, no. 1, pp. 129–140, 2017.

[9] M. Talaty, A. Esquenazi, and J. E. Briceno, "Differentiating ability in users of the rewalk tm powered exoskeleton: An analysis of walking kinematics," in 2013 IEEE 13th international conference on rehabilitation robotics (ICORR). IEEE, 2013, pp. 1–5.

[10] F. Rasouli and K. B. Reed, "Walking assistance using crutches: A state of the art review," Journal of Biomechanics, vol. 98, p. 109489, 2020.

[11] A. J. Smith, B. N. Fournier, J. Nantel, and E. D. Lemaire, "Estimating upper extremity joint loads of persons with spinal cord injury walking with a lower extremity powered exoskeleton and forearm crutches," Journal of Biomechanics, p. 109835, 2020.

[12] L. L. Haubert, D. D. Gutierrez, C. J. Newsam, J. K. Gronley, S. J. Mulroy, and J. Perry, "A comparison of shoulder joint forces during ambulation with crutches versus a walker in persons with incomplete spinal cord injury," Archives of physical medicine and rehabilitation, vol. 87, no. 1, pp. 63–70, 2006.

[13] M. M. Pink and J. E. Tibone, "The painful shoulder in the swimming athlete," Orthopedic Clinics of North America, vol. 31, no. 2, pp. 247–261, 2000.

[14] H. Van der Hoeven and W. B. Kibler, "Shoulder injuries in tennis players," British Journal of Sports Medicine, vol. 40, no. 5, pp. 435–440, 2006.

[15] J. Fong, E. B. Küçüktabak, V. Crocher, Y. Tan, K. M. Lynch, J. L. Pons, and D. Oetomo, "CANopen Robot Controller (CORC): An open software stack for human robot interaction development," in International Symposium on Wearable Robotics. Springer, 2020, pp. 287–292.