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ORIGINAL ARTICLE

Effects of rolling resistances on handrim kinetics during the performance of wheelies among manual wheelchair users with a spinal cord injury

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Study design: Repeated cross-sectional study.

Objectives: To compare the effects of rolling resistances (RRs) on handrim kinetic intensity at the non-dominant upper limb and on handrim kinetic symmetry during wheelies performed by manual wheelchair users (MWUs) with spinal cord injury (SCI).

Setting: Pathokinesiology Laboratory.

Methods: Sixteen individuals with SCI who were able to perform wheelies participated in this study. During a laboratory assessment, participants randomly performed wheelies on four RRs: natural high-grade composite board, 5-cm thick soft foam, 5-cm thick memory foam, and with the rear wheels blocked by wooden blocks. Four trials were conducted for each of the RRs. Participant's wheelchair was equipped with instrumented wheels to record handrim kinetics, whereas the movements of the wheelchair were recorded with a motion analysis system.

Results: The net mean and peak total forces, including its tangential and mediolateral components, were greater during take-off compared with the other phases of the wheelie, independently of RR. During take-off, the greatest net mean and peak total and tangential forces were reached with the wheels blocked. Symmetrical tangential and mediolateral force intensities were applied at the dominant and non-dominant handrims.

Conclusion: Wheelies performed on low or moderate density foam generate similar forces at the handrim than on a natural surface and significantly less forces than with the wheels blocked. Hence, when teaching individuals with an SCI to perform a stationary wheelie, the use of low or moderate density foam represents a valuable alternative for minimizing upper limb effort and may also optimize quasi-static postural steadiness.

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Keywords: kinetics; paraplegia; rehabilitation; rolling resistance; wheelchair; wheelie

INTRODUCTION

Achieving the ability to maintain balance on the rear wheels of a manual wheelchair during a short or long period of time, once the front wheels have intentionally left the ground (known as a '*stationary wheelie*'), is a key goal for individuals with a spinal cord injury (SCI). The ability to perform wheelies independently will facilitate the acquisition of many other advanced manual wheelchair skills (for example, crossing door steps, descending curbs and going down slopes)[1] and may have numerous beneficial health-related effects (for example, preservation of skin integrity at the buttocks and reduced neck discomfort or pain).[2,3] Surprisingly, rehabilitation professionals still allocate limited time for improving this complex wheelchair skill during intensive functional rehabilitation for various reasons[1] and only a limited number of individuals with an SCI (about 4%) master this skill upon completion of rehabilitation.[4] However, proper training of this skill, as proposed in the Wheelchair Skill Training Program (refer to www.wheelchairskillsprogram.ca), has been shown to increase the skill learning success rate.[5]

To improve mastery of this complex wheelchair skill in clinical practice, it has been suggested that wheelies should be performed on various rolling resistances (RRs) when training individuals with an SCI. In one study, increasing the RR reduced the perceived difficulty during the balance phase and decreased rear-wheel displacement during the take-off and balance phases of the wheelie among able-bodied individuals.[6] Another group found that increasing the RR neither improved the success rate nor reduced the learning time when teaching wheelies to able-bodied individuals.[7] Although a few studies have investigated the performance of wheelies among able-bodied individuals,[1,8] the effect of varying RRs on handrim kinetics during wheelies has not been extensively studied among individuals with an SCI.

The purpose of the present study was to compare the effects of four distinct RRs on the intensity of the handrim kinetic measures at the non-dominant upper limb (U/L) and on the symmetry of these measures (that is, dominant versus non-dominant U/Ls) during the execution of wheelies among manual wheelchair users (MWUs) with

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Table 1 Demographics and clinical characteristics of participants

No.	Gender	Age (years)	Height (m)	Weight (kg)	Neurological level	ASIA	Motor ASIA (/100)	Sensory ASIA (/224)	Time since injury (years)
1	M	40.0	1.78	75.3	C7	C	60	148	4.8
2	M	34.8	1.80	78.7	T6	C	91	194	10.8
3	M	37.1	1.52	85.6	T6	B	50	166	6.6
4	M	47.7	1.83	57.7	T2	A	50	80	26.2
5	M	31.9	1.75	63.9	T4	A	50	95	7.9
6	M	58.5	1.70	64.6	T5	A	50	92	36.0
7	M	38.0	1.63	59.5	T7	A	50	106	4.3
8	M	43.4	1.84	82.7	T7	A	50	119	9.7
9	M	22.3	1.83	57.5	T8	A	50	119	1.2
10	M	58.8	1.88	94.7	T10	A	50	140	3.9
11	M	31.2	1.91	94.5	T10	A	50	140	4.3
12	M	45.5	1.73	78.0	T10	A	50	140	3.7
13	M	33.9	1.80	79.6	T11	A	50	148	8.4
14	F	27.1	1.65	46.3	T11	A	50	148	3.7
15	M	27.3	1.85	67.7	T12	A	50	156	9.5
16	M	32.2	1.93	71.8	T12	A	56	154	6.8
Mean		38.1	1.78	72.4			53.5	134.1	9.2
S.d.		10.5	0.11	13.8			10.4	30.2	9.1

an SCI. It was hypothesized that the performance of stationary wheelies would require greater force application on the handrim as the RR progressively increased. It was also anticipated that symmetrical handrim force applications would be generated during the execution of wheelies. The choice of only assessing the non-dominant U/L was based on the notion that it limits performance when realizing a bilateral functional task requiring quasi-symmetric U/L efforts.

MATERIALS AND METHODS

Participants

Sixteen individuals, who sustained an SCI at least 1 year before the study, used a manual wheelchair as their primary mean of mobility (>4 h/day), were able to perform wheelies independently and did not suffer from shoulder pain (mean Wheelchair User Shoulder Pain Index (WUSPI) score = 0.11 ± 0.15/10)[9,10] volunteered to participate in this study (Table 1). They were excluded if they had associated neurological conditions (for example, peripheral neuropathy), musculoskeletal impairments (for example, rotator cuff tendinopathy) or any other impairment that could have hindered their ability to carry out the experimental tasks. Ethical approval was obtained from the Research Ethics Committee of the Center for Interdisciplinary Research in Rehabilitation of Greater Montreal. Participants reviewed and signed informed consent forms before entering the study.

Clinical assessment

Before the experiment, participants underwent a clinical assessment completed by a physiotherapist who has over 10 years of clinical experience working with individuals with SCI. This assessment included the participants' personal characteristics (for example, age, time since injury and experience with a wheelchair), anthropometric parameters (for example, size and weight), neurological level and completeness of the SCI (American Spnail Injury Association (ASIA) sensory and motor impairment scale), and integrity of upper limb (U/L) segments (for example, WUSPI, passive and active range of motion assessment and manual muscle testing).

Experimental tasks

When instructed to perform wheelies, participants were asked to lift their front wheels off the floor, then balance on their rear wheels for ∼25–30 s (that is, participants achieve a high level of proficiency) and finally lower their front wheels back on the floor using their usual technique. Wheelies were performed on four different surfaces following a randomized sequence. Each of these four different surfaces represented a distinct RR (Figure 1): (1) natural surface consisting of a painted high-grade smooth composite board (NAT); (2) 5-cm thick urethane regular soft yellow foam (LOW); (3) 5-cm Rolyan Temper Foam (Patterson Medical, Bolingbrook, IL, USA) medium visco-elastic pink memory foam (MOD); and (4) two 5-cm high wooden blocks with the rear wheels completely blocked (HIGH). Four wheelies were completed on each of the four different RRs. For each of these RRs, a familiarization period was allowed before the wheelie was recorded. Participants used their own wheelchair. For safety reasons, a spotter strap attached to the participant's wheelchair was held by a therapist positioned close to the participant.

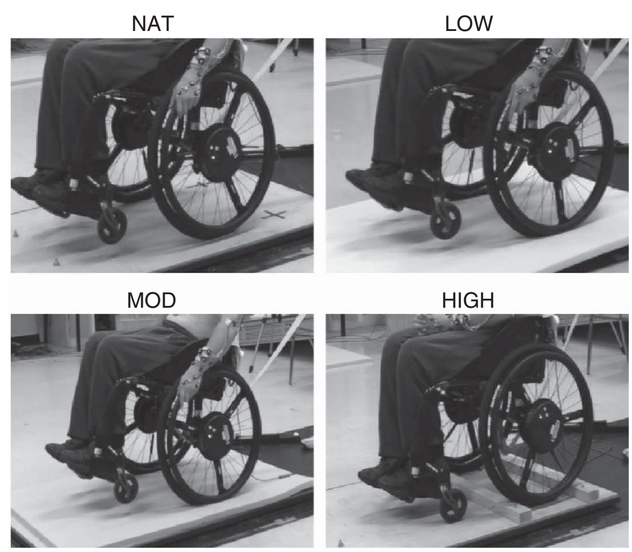

Figure 1 Overview of the experimental tasks and rolling resistances (NAT, natural surface; LOW, regular soft yellow foam; MOD, medium visco-elastic pink memory foam; HIGH, rear wheels completely blocked by two wooden blocks).

Handrim kinetics

The wheelchair was equipped with two instrumented wheels to measure and amplify the handrim forces and moments at 240 Hz (SmartWheel; Three River Holdings, Mesa, AZ, USA). These instrumented wheels, once installed on the

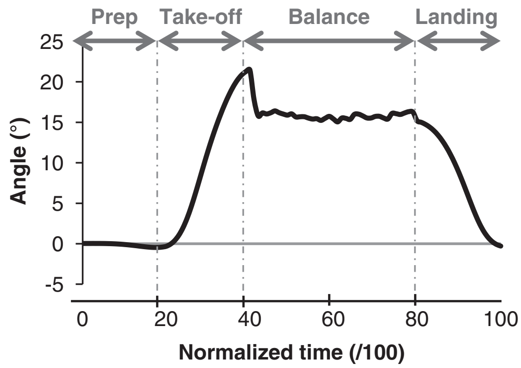

Figure 2 Summary of the time events used to define the phases of the wheelie with respect to the angle (°) between the wheelchair frame and the ground surface: preparation (20%), take-off (20%), balance (40%) and landing phases (20%).

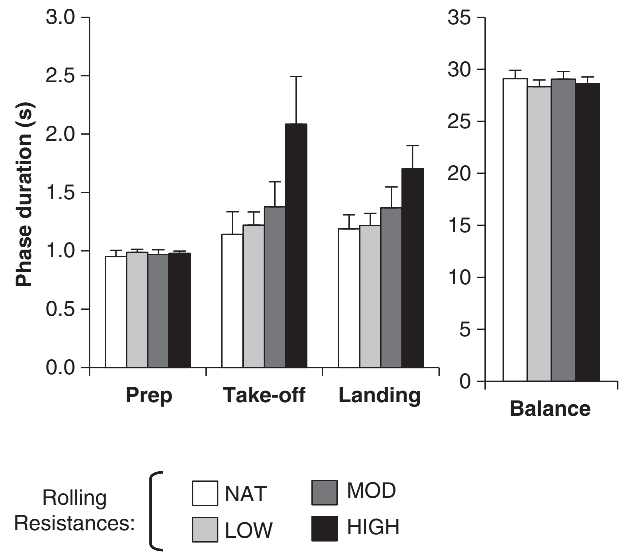

Figure 3 Group mean ± s.d. of the absolute duration of the phases measured during wheelie on four rolling resistances.

participant wheelchair, did not significantly alter wheelchair characteristics (width, position, size and orientation of the wheels) aside from the overall weight of the wheelchair (SmartWheel = 4.9 kg/wheel). Handrim kinetic data were sent in real time by telemetry to a computer and continuously recorded with the SmartWheel Software 2010 program (Three River Holdings, Mesa, AZ, USA). Synchronization of the two SmartWheels with a motion capture system was done by synchronizing off line the vertical force peaks produced simultaneously on the two handrims with an instrumented hammer strike. Forces and moments were first filtered using a zero-lag second-order Butterworth filter with a cutoff frequency of 20 Hz and then downsampled to 30 Hz to align with kinematic data. The resultant force (F_{tot}) and the tangential component of the resultant force (F_{tg}), known to directly contribute to the forward/backward rotation of the wheel, were calculated.

Wheelchair kinematics

Wheelchair kinematics were recorded during wheelie movements at a sampling frequency of 30 Hz using an Optotrak motion analysis system consisting of four synchronized camera units (model 3020; NDI Technology Inc., Waterloo, ON, Canada). This system tracked the three-dimensional (3-D) coordinates of four infrared light-emitting diodes fixed to the wheelchair frame (for example, left and right anterior and posterior parts of the frame). Additionally, 16 specific wheelchair landmarks were digitized with a six-marker probe for further definition of the wheelchair frame and instrumented wheels within the global laboratory referential. All marker trajectories were visually inspected to identify missing marker coordinates and, when possible, their coordinates were interpolated using a linear or cubic spline method.

Phases of the wheelie

To facilitate analysis, each wheelie movement was divided into four phases and time normalized to 100%. The phases were as follows: preparation (20%), take-off (20%), balance (40%) and landing (20%),[1,11] (Figure 2). These phases were determined based on the angle formed between the wheelchair frame and the ground surface and further validated by the velocity of the wheelchair. The preparation phase started 1 s before take-off of the front wheels. The take-off and landing phases were automatically determined when the angular velocity of the wheelchair was positive and negative, respectively. A balance phase occurred between these two phases.

Outcome measures

The total force (F_{tot}) was determined by computing the vectorial sum of the individual forces (F_x, F_y and F_z) measured at the handrim on the non-dominant side,[12] which is considered to limit the performance of a functional task requiring bilateral symmetrical efforts, such as a wheelie.[13] The tangential force (F_{tg}) was obtained using Cooper *et al.*'s method using the determination of point of force application.[14] The point of force application was assumed to be at the projection of the hand center of mass on the handrim.[15] The maximal rate of rise is the peak velocity reached by F_{tot} during the take-off phase, and was calculated by taking the maximal value of the F_{tot} derivative with respect to time.[16] The minimal and maximal values of the main outcome measures as well as their excursion were calculated for each phase of the wheelie on each of the four RRs. These main outcome measures were selected as they are likely related to the development of secondary musculoskeletal impairments affecting the U/Ls among wheelchair users.[16]

A *symmetry index intensity*, expressed as a percentage, was also calculated to verify if similar forces were applied at the dominant and non-dominant handrims:[17]

$$\text{Symmetry index intensity (\%)} = (F_{dom}/(F_{dom+}F_{nondom}))\times 100$$

where F_{dom} and $F_{non\text{-}dom}$ correspond to the absolute force applied on the dominant and the non-dominant handrims, respectively. A value ranging between 45% and 55% indicates near-perfect symmetry, whereas a value of $\leqslant$45% or $\geqslant$55% reflects greater force application at the non-dominant or dominant handrim, respectively. Finally, a *symmetry index direction* was computed for the tangential and mediolateral forces to verify if the dominant and non-dominant handrim forces were applied in the same direction. To do so, a dichotomous variable (0 = forces applied in opposite directions and 1 = forces applied in the same direction) was computed at each of the 100 data point defining the wheelie.

Statistical analysis

Descriptive statistics (mean ± s.d.) were calculated for demographics, clinical characteristics of the participants and the selected outcome measures. After confirming the normality of the data distribution, a two-way analysis of variance for repeated measures represented by four levels (four phases (preparation, take-off, balance, landing) × four RRs (NAT, LOW, MOD, HIGH)) was used to verify whether differences existed across phases or between RRs. The main effects of each factor were reported when indicated with a statistical significance threshold set at 0.05. In the presence of a significant interaction effect between the two factors, *post-hoc* Tukey tests were conducted using an adjusted statistical threshold set at 0.008 (*P*-value = 0.05/6 possible pairwise comparisons = 0.008). Statistical analyses were performed with the Statistica v.10 software (SatSoft, Tulsa, OK, USA).

RESULTS

Duration of phases

The preparation, take-off, balance and landing phases lasted, on average, 0.97 ± 0.02 s, 1.5 ± 0.4 s, 28.7 ± 0.4 s and 1.4 ± 0.2 s for all RRs,

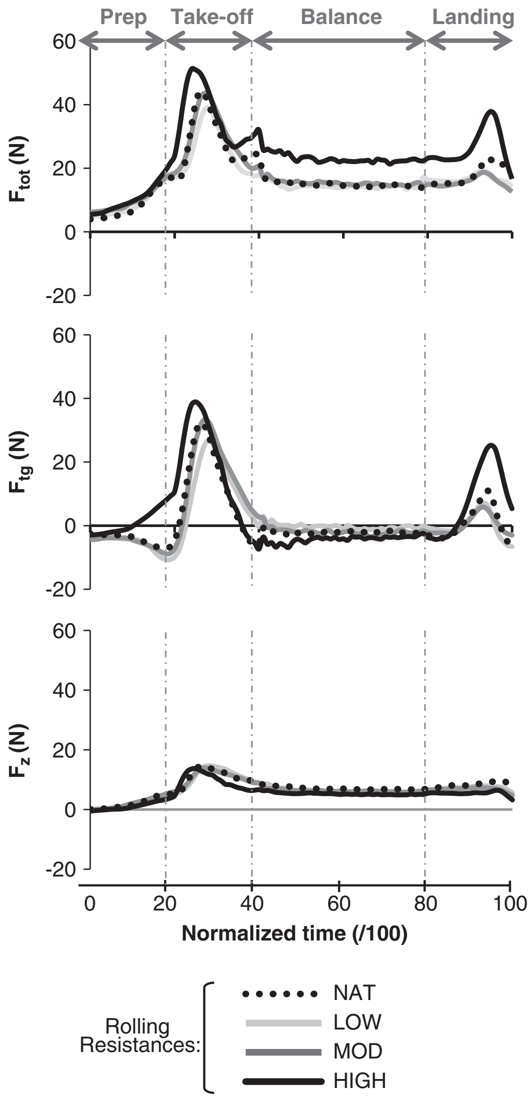

Figure 4 Time-normalized group mean values of the F_{tot}, F_{tg} and F_z with respect to time measured during wheelie on four rolling resistances.

respectively (Figure 3). When the wheelie was performed with the wheels blocked (HIGH), the duration of the take-off ($P = 0.00018$–0.00101) and landing ($P = 0.00018$–0.00528) phase was greater compared with the duration measured with the other three RRs (take-off: +71 to 94%; landing: +33 to 51%). No significant difference was found among the RRs for the other phase durations.

Forces applied at the handrim

The F_{tot}, F_{tg} and F_z patterns applied at the handrim by the non-dominant U/L, during the different phases of the wheelie and across the different RRs, are summarized in Figure 4. In general, the F_{tot} and F_{tg} patterns are greater when wheelies are performed with the wheels blocked (HIGH) compared with the other RRs. During the preparation phase, F_{tg} patterns show a forward force application with the wheels blocked (HIGH) compared with a quick backward force application for the other RRs before the lift-off phase. The F_z patterns, which confirm a force applied medially at the handrim, are lower than the F_{tg} patterns during the take-off phase while slightly greater than the F_{tg} patterns during the balance phase of the wheelie.

Effects of RR

The mean, minimal and maximal F_{tot}, F_{tg} and F_z with regard to the different RRs are summarized in Figure 5. When specifically looking at the effects of RRs, the mean and maximal F_{tot} were greater ($P = 0.001$–0.009) with the wheels blocked (HIGH) compared with the other RRs across all phases. When specifically looking at the take-off phase, the maximal F_{tot} with the wheels blocked (HIGH) was 27–36% (19–26 N) greater ($P = 0.00003$) compared with the other RRs, whereas the maximal F_{tg} with the wheels blocked (HIGH) was 28–41% (15–22 N) greater ($P = 0.00003$–0.00008) than with the other RRs. As for the descent phase, the maximal F_{tot} with the wheels blocked (HIGH) was 37–51% (18–24 N) greater ($P = 0.00003$) compared with the other RRs, whereas the maximal F_{tg} with the wheels blocked (HIGH) was 53–65% (17–21 N) greater ($P = 0.00003$) than with the other RRs. As for the mean F_z, it was similar ($P = 0.03$–0.99) across all RRs despite the fact that F_z decreased (absolute mean difference = 1.75 N) with the wheels blocked (HIGH) compared than with the NAT, independently of the phases. The maximal F_z was similar ($P = 0.19$–0.99) across all RRs. The rate of rise values calculated during the take-off phase ranged between 225.22 ± 21.45 N/s and remained similar across all RRs tested ($P = 0.25$).

Differences across phases

The mean and maximal F_{tot} were 36–67% (11–20 N) greater ($P = 0.00017$–0.00207) during the take-off phase compared with the other phases for all RRs, respectively. The mean and maximal F_{tg} were 57–98% (24–37 N) greater ($P = 0.00017$–0.00353) also during the take-off phase compared with the other phases regardless of the RR ($P = 0.16$–1.00). The minimal F_{tg} remained similar regardless of the phases ($P = 0.28$) or RR ($P = 0.95$). The mean F_z was different across all phases ($P = 0.0001$–0.008) except for the balancing and landing phases found to be similar ($P = 0.92$). The maximal F_z was greater during the take-off phase compared with the preparation ($P = 0.0002$) and landing phases ($P = 0.0016$), but similar to the balance phase ($P = 0.02$), for all RRs.

Intensity and direction symmetry indices

The symmetry index *intensity* patterns for the F_{tot}, F_{tg} and F_z are summarized in Figure 6. Overall, these patterns highlight comparable force application at the dominant and non-dominant handrims during the wheelies, especially during the balance phase. In fact, similar mean symmetry indices were found ($P = 0.26$–1.0) between the different RRs, whereas different mean symmetry indices occurred across the different phases. The F_{tot} and F_z mean symmetry indices during the preparation phase were slightly lower ($P = 0.0003$–0.002) compared with the balance and landing phases, regardless of the RRs. No significant difference ($P = 0.07$–0.99) was found for F_{tg} across the different phases. As for the symmetry index-*direction* patterns, they reveal that the tangential and mediolateral forces measured at the dominant and non-dominant handrims are predominantly applied in the same direction during the take-off phase. As for the balance phase, the mediolateral forces are predominantly applied in the same direction, whereas the F_{tg} is frequently applied in opposite directions, especially when balancing wheelies on the natural surface (NAT) or on LOW RR.

DISCUSSION

Blocking rear wheels increases effort

Performing a stationary wheelie when the rear wheels were blocked required more U/L efforts than when doing so with the rear wheels

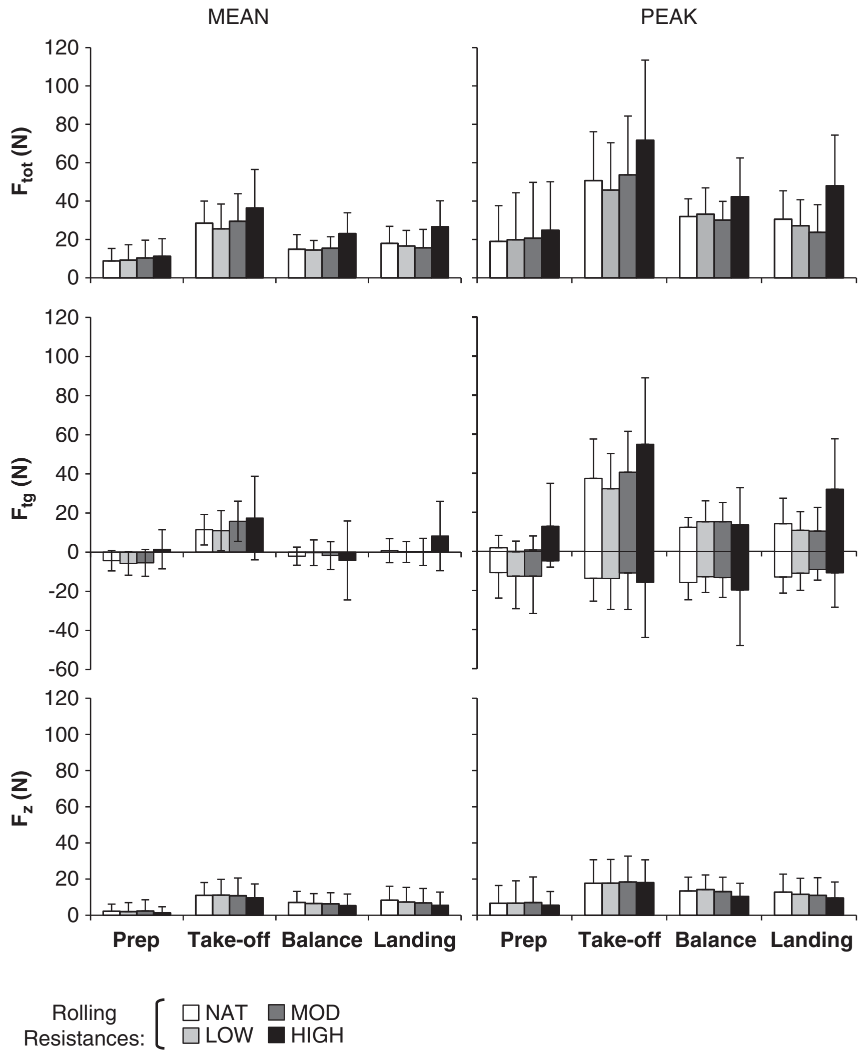

Figure 5 Summary of mean and peak values ± s.d. for the F_{tot}, F_{tg} and F_z measured during the different phases of the wheelie on four rolling resistances.

unlocked, independently of the surfaces (natural or foam). The fact that the rear wheels were blocked prevented participants from producing a rapid backward force (negative F_{tg}), which generates backward momentum, before generating a forward force (positive F_{tg}) needed to lift the front wheels off the floor as observed when the wheels were unlocked. The intensity and timing of the posterior force due in part to the inertial effect of the body and wheelchair mass may facilitate the wheelchair backward tilt upon the application of a rapid forward force (positive F_{tg}). This may explain why the F_{tg} rose at a slower rate during the preparation phase and reached its greatest value during the take-off phase with the wheels blocked. Moreover, the fact that the wheels were blocked required participants to apply a forward force to lift the front wheels and symmetrical anteroposterior forces to dynamically control balance as the forward displacement of the wheelchair and the other degrees of freedom were restricted (that is, mediolateral). Also, the fact that the wheelchair could not move to modify the base of support while maintaining stability has to be taken into account. The reduced perceived exertion previously documented when performing wheelies may also corroborate the present findings.[6] Hence, performing a wheelie with the rear wheels blocked requires different strategies than doing so on a natural surface or on foam with various densities.

Symmetrical intensities and asymmetrical direction during wheelies

Although the intensity of the absolute forces applied at the dominant and non-dominant handrims by the upper limbs was mostly symmetric during the performance of wheelies, the direction of these forces deserves attention. During the take-off phase, substantial forward (F_{tg}) and medial (F_z) forces of similar intensity are applied in the same direction at the handrims to generate sufficient force to lift the front wheels off the floor. Thereafter, during the balance phase, medial (F_z) forces of similar intensity are applied in the same direction at the handrims whereas asymmetric F_{tg} (for example, intensity and direction) is observed, especially on the natural and low RR surfaces. These forward-backward force application asymmetries between the rear wheels of the wheelchair, considered as a counter-steering mechanism, trigger series of oscillations that may enlarge the geometric base of support and, in turn, proactively and dynamically stabilize the wheelie by preserving the center of mass of the system (wheelchair and individual with SCI) over its functional base of support while remaining quasi-stationary.[11] The fact that the F_{tg} was predominantly symmetric (that is, intensity and direction), when the rear wheels were locked, further supports this point and confirms the complexity of this motor task. As for the asymmetry observed during

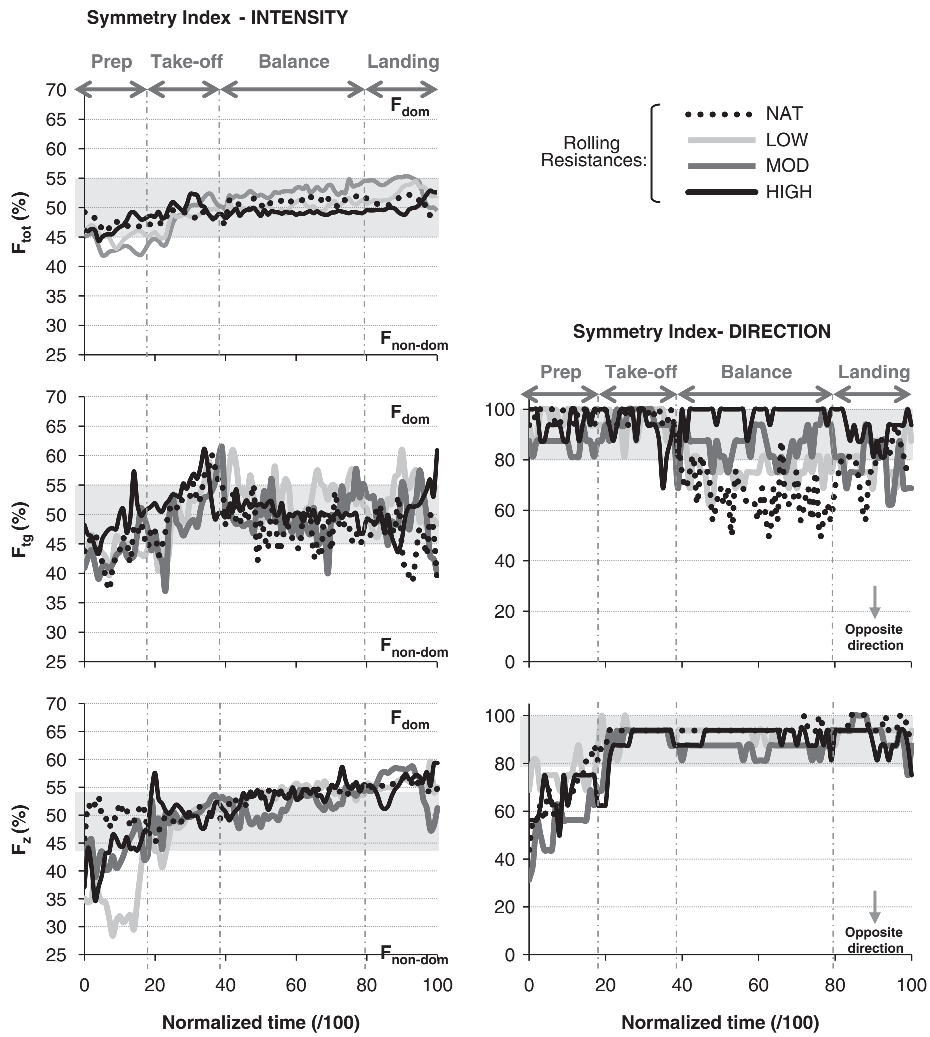

Figure 6 Time-normalized group mean values of the F_{tot}, F_{tg} and F_z symmetry index-intensity patterns as well as of the mean symmetry index direction for the F_{tg} and F_z. Note that the area highlighted in light gray on the graphs represents a zone of symmetry for the intensity or for the direction.

Table 2 Peak F_{tot} and F_{tg} during wheelie take-off phase and propulsion

	Tasks	*Peak* F_{tot}(N)	*Peak* F_{tg}(N)
Present study	Wheelie take-off	50.1 ± 25.7	37.8 ± 21.8
Boninger *et al.* [16]	Propulsion 1 ± 0.1 m/s	67.3 ± 24.8	36.1 ± 17.8
	Propulsion 1.6 ± 0.2 m/s	94.5 ± 31.2	43.7 ± 20.5

the preparation phase, it most likely results from the low forces measured at the handrims during this phase. Hence, only a small alteration can lead to a great percentage difference, particularly during the preparation phase.

Wheelie requires similar effort as propulsion

To better understand the U/L effort related to the performance of wheelies, it appears useful to compare the forces obtained in the present study with those previously reported in other studies for manual wheelchair propulsion. To this effect, the handrim kinetic results (that is, peak F_{tot} and F_{tg}), reported by Boninger *et al.*[16] following the assessment of manual wheelchair propulsion at natural speed among individuals with an SCI, were used as reference values (Table 2). Interestingly, to perform a wheelie the user must apply comparable forces at the handrim as those applied during manual wheelchair propulsion. However, these forces are not applied as frequently during a wheelie as they are during manual wheelchair propulsion. In fact, recent studies reported average distances ranging from 1700 to 2500 m/day among MWUs with an SCI,[18–20] which requires a similar number of strokes (~1 m/stroke). Despite the similar intensity, yet different frequency at which wheelies are performed, wheelies may present less U/L risk exposure than manual wheelchair propulsion. However, other risks related to wheelies (that is, falls) should not be underestimated. To this effect, it is also probable that the fear of fall, even the anticipation of being unable to transfer back from the floor into their wheelchair in case of a fall, may hamper the ability to independently perform wheelchair wheelie.

Limitations

This study presents limitations that need to be considered when interpreting the results. The fact that the sample size was relatively small ($n = 16$) and that all participants were well-experienced MWUs with an SCI and tested in their own personal wheelchair (for example, wheelchair configuration differences) may limit the possibility of generalizing the results of the present study for the entire population or specific subgroups of MWUs, especially those with a recent SCI undergoing intensive functional rehabilitation. The fact that wheelies were performed in a laboratory environment and that instrumented wheels were used may have altered the participants' usual performance. The fact that only four distinct RRs were assessed may also not be representative of all RRs encountered in daily life. Last, the low frequency (30 Hz) used for the kinematic analysis restricts the capability to further analyze the balance strategies during the wheelie.

Conclusion

When specifically training the ability to balance on the rear wheels, completely blocking the wheels may be indicated, particularly if the therapist wishes to assist individuals with an SCI during the lift-off and landing phase to minimize U/L efforts. Alternatively, since performing stationary wheelies over foam requires similar U/L efforts as doing so on a natural surface, training individuals with an SCI to perform wheelies over foams (that is, LOW and MOD RR) may represent a valuable alternative in clinical practice, especially that the acquisition of force application strategies (motor skills) optimizing postural steadiness may simultaneously be facilitated. Such an exposure to various RRs in clinical practice should also be encouraged as it may allow individuals with SCI to positively adapt handrim force intensity and symmetry when performing wheelies in everyday life in various physical environments (that is, RRs) that differ from the ones encounters during rehabilitation. Future studies incorporating U/L kinematics, kinetics and electromyographic analysis could definitively strengthen the results of the present study and provide additional evidence-based knowledge that may influence the way this manual wheelchair skill is taught to individuals with an SCI or other manual wheelchair users in clinical practice.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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