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Biomechanic Evaluation of Upper-Extremity Symmetry Manual Wheelchair Propulsion Over Varied Terrain

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Abstract

Objective—To evaluate upper-extremity symmetry during wheelchair propulsion across multiple terrain surfaces.

Design—Case series.

Setting—A biomechanics laboratory and the community.

Participants—Manual wheelchair users (N=12).

Interventions—Not applicable.

Main Outcome Measures—Symmetry indexes for the propulsion moment, total force, tangential force, fractional effective force, time-to-peak propulsion moment, work, length of push cycle, and power during wheelchair propulsion over outdoor and indoor community conditions, and in conditions.

Results—Upper-extremity asymmetry was present within each condition. There were no differences in the magnitude of asymmetry when comparing laboratory with indoor community conditions. Outdoor community wheelchair propulsion asymmetry was significantly greater than asymmetry measured during laboratory conditions.

Conclusions—Investigators should be aware that manual wheelchair propulsion is an asymmetrical act, which may influence interpretation when data is collected from a single limb or averaged for both limbs. The greater asymmetry identified during outdoor versus laboratory conditions the emphasizes need to evaluate wheelchair biomechanics in the user's natural environment.

Keywords

Biomechanics; Rehabilitation; Upper extremity; Wheelchairs

THE BILATERAL NATURE of wheelchair propulsion places both upper extremities at risk for overuse injury. Upper-extremity pain[1-3] and overuse injury[4-6] are common in manual wheelchair users. Limb pain is frequently associated with activities of daily living[2,3,7] and is hypothesized to be a consequence of repetitive wheeling (eg, manually propelling a wheelchair) and upper-extremity weight bearing activities. The novel mode of ambulation

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and potential deleterious impact on function has consequently made wheelchair propulsion the focus of many biomechanic investigations.

Measurement of propulsion force is now possible with instrumented wheelchair rims. The technology is, however, expensive. Often investigators are able to purchase only 1 instrumented rim, limiting studies to evaluation of 1 extremity. Investigators who have collected bilateral upper-extremity kinetic data during wheelchair propulsion subsequently averaged the data for both limbs[8-10] or have selected only 1 limb for analysis.[11] This suggests that side-to-side differences during wheelchair propulsion are not meaningful. However, in a study of pushrim propulsion patterns, Boninger et al[12] alanalyzed left and right upper extremities separately and reported that several subjects had different propulsion patterns between extremities. They stated “assuming that the left and right sides are identical may lead to errors.” Conditions, however, were limited to evaluation of propulsion while the study participant’s wheelchair was secured to a dynamometer. We have found no studies that have evaluated side-to-side differences in propulsion biomechanics across varied terrain.

Wheelchair propulsion asymmetry may have clinical consequences. In this population, both upper extremities are at high risk for pain and injury as a consequence of the bilateral demands of propulsion and weight relief. Curtis et al[3] studied the prevalence and intensity of shoulder pain during functional activities in manual wheelchair users, and reported that the majority of manual wheelchair users with paraplegia (34%) experienced bilateral upper-extremity pain. A large number of subjects, however, stated that they had pain in only 1 arm (24%).[3] Risk factors for unilateral upper-extremity pain in the manual wheelchair user have not been identified. Perhaps the presence of upper-extremity propulsion asymmetry may be a contributing factor to the development of injury in the manual wheelchair manual user.

Studies evaluating manual wheelchair propulsion kinetics,[13-19] technique,[12,18,20-23] and the impact of propulsion biomechanics on injury[8,9,11] have traditionally been performed in laboratory conditions. Laboratory terrain surfaces have consisted of level tile floor surfaces or wheelchair dynamometers. Few studies have investigated wheelchair propulsion tasks that capture indoor and outdoor community ambulation conditions. The type of terrain surface and surface inclination angle have, however, been shown to impact propulsion kinetics, velocity, and stroke pattern.[16,17,23,24] These results emphasize the imporontance of evaluating wheelchair propulsion over a range of conditions.

Evaluating both extremities during wheelchair propulsion in a variety of conditions is critical to gaining a comprehensive understanding of the biomechanics of wheeling, and the impact manual wheelchair use may have on upper-extremity injury. Therefore, the purpose of this study was to evaluate upper-extremity symmetry during wheelchair propulsion across typical laboratory, indoor, and outdoor terrain surfaces. Based on the high incidence of unilateral shoulder pain in manual wheelchair users, and Boninger et al’s previous description[12] of side-to-side differences in propulsion, we hypothesized that propulsion within all conditions would be an asymmetrical task. We also hypothesized that upper-extremity symmetry measured during laboratory conditions would not be representative of community wheelchair ambulation. Specifically, we predicted propulsion symmetry would be greater during laboratory conditions compared with indoor and outdoor community conditions. The rationale in this instance was that, as wheeling conditions became more challenging, side-to-side differences would become magnified.

METHODS

Participants

Subjects were recruited using public advertisements and admission records from a large outpatient SCI clinic. Study inclusion criteria included subject age between 18 and 65 years, a minimum of 1 year of experience as a manual wheelchair user, and an occupation that did not involve repetitive overhead activities. Before testing all subjects underwent a physical examination by a licensed physical therapist to identify the presence of upper-extremity impairments and/or pathology. Study exclusion criteria included findings of incomplete upper-extremity range of motion, muscle weakness, current or chronic upper-extremity pain, or a history of significant upper-extremity injury (eg, rotator cuff tear, dislocation, fracture). Study participants self-reported their dominant upper extremity. The study protocol was approved by the Mayo Clinic Institutional Review Board and informed consent was obtained from all research participants before initiating test procedures.

Data Collection

Prior to each data collection, 2 instrumented SmartWheel rims[a] were attached to the subject's wheelchair. The rims were subsequently used during testing to measure bilateral upper-extremity kinetic and temporospatial data for each stroke. The SmartWheel is a commercially available, wireless, force- and torque-sensing pushrim that may be used to examine 3-dimensional forces (F_x, F_y, F_z), moments (M_x, M_y, M_z), and temporospatial (eg, contact time, velocity) characteristics of manual wheelchair propulsion. The SmartWheel coordinate system is defined with *x* representing forward progression, *y* representing the axis perpendicular to the floor pointed superiorly, and *z* pointing out of the wheel along the axle. The precision (2N) and resolution (0.2N) of the SmartWheel rims have previously been established.[25] Application of the rims did not alter any of the wheelchair settings.

The testing procedure encompassed manual wheelchair propulsion during 8 conditions, including outdoor and indoor community terrain, and laboratory terrain. All propulsion tasks were performed at the subject's self-selected pace. The outdoor community terrain was a single, continuous, 500-m concrete sidewalk course comprising 4 conditions performed in the following order: (1) 2° right cross-slope (right-side lower), (2) smooth level, (3) aggregate (ie, textured surface) level, and (4) 3° ramp (1:19 rise to run) with a smooth surface. Indoor community terrain testing included, in order, 2 separate 10-m conditions composed of a level low-pile carpet surface and a 4.8° ramp (1:12 rise to run) with a low-pile carpet surface. Laboratory terrain included a 10-m long smooth level tile surface and a dynamometer with a level surface. The outdoor sidewalk course was completed once. Three trials each were performed for all 10-m indoor conditions, and 1 trial 30 seconds in length was performed for the dynamometer condition. The outdoor sidewalk course and indoor carpet conditions were chosen because these tasks are representative of terrain surfaces encountered during community wheelchair ambulation. The tile surface and dynamometer were chosen because these conditions are most commonly used during laboratory investigations of wheelchair propulsion. In all instances the testing terrain required the subject to propel the chair in a straight-ahead direction (ie, there were no turns or curves).

Data Management

All kinetic data were sampled at 240Hz and low-pass filtered at 30Hz with an eighth-order, zero-lag digital Butterworth filter.[26] Force data were normalized to subject body mass. The interval of interest was the push phase of wheelchair propulsion, with the onset of push

[a]**Suppliers** Three Rivers Holdings, 1826 W Broadway Rd, #43, Mesa, AZ 85202.

defined as M_z greater than 0 and off as M_z is equal to 0.[27] Three consecutive, representative push cycles from the steady propulsion state within each condition were then identified. Using the propulsion moment (M_z), a custom computer algorithm[b] with visual confirmation was used to identify push cycles of the dominant extremity with the smallest average absolute deviation from the median propulsion moment:

$$\frac{1}{n}\sum_{i=1}^{n}|x_i - \tilde{x}|$$

where x_i is peak M value for single push cycle; $\tilde{x}$ is median peak M_z for entire trial; and n equals 3.

Data for the 3 consecutive push cycles were averaged, and the average for each extremity was used for analysis. Data from the 3 push cycles in the 3 trials performed for the 10-m indoor conditions were averaged for analysis.

Variables that captured propulsion timing, effort, and force were chosen for analysis (table 1). All variable calculations were derived from kinetic data obtained from the 2 Smart-Wheel rims and custom MatLab programs. To evaluate upper-extremity symmetry during propulsion, a symmetry index was calculated for each variable[28] as follows:

$$\left|\left(1-\left(\frac{D}{ND}\right)\right)\right|$$

where *D* denotes the dominant upper extremity and *ND* denotes the nondominant upper extremity.

With this calculation technique smaller values represent greater symmetry (perfect symmetry is 0). This symmetry index was selected because it was designed to allow the data to form a normative or Gaussian distribution. This index overcomes problems of simpler indices that lack linearity and thus are unacceptable for statistical purposes.[29]

Statistical Analysis

Within-condition wheelchair propulsion symmetry was evaluated with a 1-sample *t* test, comparing symmetry indexes with a test value of 0 (perfect symmetry). Between-condition wheelchair propulsion symmetry was evaluated for each variable of interest with a repeated-measures analysis of variance, including 8 between factors (condition) and 1 repeated factor (subject). When significant main effects were found, post hoc contrast statements were conducted to evaluate differences between conditions. The first contrast statement compared within-laboratory conditions to determine whether each task (tile, dynamometer) should be considered as separate versus combined laboratory variables. The concern was that wheelchair dynamometers may present users with the unique challenge of constant linear momentum generation demands (ie, propulsion on a tiled floor results in a greater rolling distance during push recovery, but there is no linear momentum during dynamometer propulsion), thus making the dynamometer a distinct laboratory condition. Subsequent contrast statement analyses were consistent with our a priori hypotheses, including comparison of (1) laboratory (tile, dynamometer) versus indoor community (level carpet, indoor ramp) conditions, and (2) laboratory versus outdoor community (cross-slope, smooth

[b]The MathWorks Inc, 3 Apple Hill Dr, Natick, MA 01760-2098.

concrete, aggregate concrete, outdoor ramp) conditions. For all analyses statistical significance was established at *P* less than .05. Statistical testing was performed using commercially available software.[c]

RESULTS

The 12 subjects comprising the study sample included 11 men and 1 woman. Subjects were on average 43±6.4 years old (range, 29–56y) with 18±9 years of experience as a manual wheelchair user (range, 1–29y). Eleven of the subjects were wheelchair users secondary to SCI (range, T4–L10), and 1 secondary to spina bifida. Ten subjects were right-hand dominant; 2 were left-hand dominant.

Within each condition (cross-slope, smooth concrete, aggregate concrete, outdoor ramp, carpet, indoor ramp, tile, dynamometer), symmetry indexes were statistically significant for all variables (table 2). Between conditions, symmetry indexes were also significantly different for all variables (propulsion moment, $P<.001$; total force, $P=.004$; tangential force, $P<.001$; fractional effective force, $P<.001$; time-to-peak propulsion moment, $P=.001$; work, $P<.001$; contact, $P<.001$; power, $P<.001$). Post hoc contrast statements indicated that there were no differences in the symmetry index for within-lab conditions (tile vs dynamometer) for any variables (fig 1). Subsequent contrast statements were therefore performed with tile and dynamometer tasks combined to represent the lab condition. There were no significant differences in the symmetry index between lab and indoor community conditions for any variables (see fig 1). Comparison of lab and outdoor community conditions resulted in significant differences in symmetry indexes for all variables (outdoor > lab) with the exception of time-to-peak propulsion moment ($P=.188$) (see fig 1).

DISCUSSION

This study has shown that manual wheelchair users with no pain or upper-extremity injury exhibit asymmetry during propulsion, with the magnitude of asymmetry impacted by the wheeling environment. These findings were consistent for variables that captured propulsion timing, effort, and force. As we predicted, propulsion asymmetry was identified during all laboratory, indoor community, and outdoor community conditions. Our hypothesis that symmetry measured during laboratory conditions would not be representative of community wheelchair ambulation was partially supported by the results. The magnitude of propulsion asymmetry was significantly different during outdoor tasks compared with laboratory tasks. There was no difference, however, between indoor community and laboratory symmetry indexes.

Within all conditions, propulsion asymmetry was identified for each variable of interest. Previously, Boninger et al[12] described side-to-side differences in propulsion patterns (based on kinematic-based categories) during evaluation of 38 manual wheelchair users with SCI. The differences in propulsion patterns described by Boninger,[12] however, occurred during the recovery phase of propulsion. Thus, there were no side-to-side kinetic differences. Additionally, Boninger's analysis[12] of differences in bilateral propulsion patterns was descriptive in nature and not based on a statistical evaluation. The current investigation is the first study known to directly evaluate the symmetry of wheelchair propulsion. The subjects comprising our cohort were free of upper-extremity injury, and testing was performed over multiple terrain surfaces and conditions. Future studies will be necessary to determine whether the magnitude of asymmetry is a significant factor contributing to, or predicting, the development of upper-extremity injury in manual wheelchair users.

[c]Version 9.1; SAS Institute Inc, 100 SAS Campus Dr, Cary, NC 27513.

We attempted to determine the role of arm dominance in propulsion asymmetry. Though there were not large differences in dominant and nondominant limb means for the group across variables and conditions, these values do not capture side-to-side differences among subjects. Therefore, we visually inspected the symmetry indexes by limb for individual subjects to determine if there was a consistent pattern in the magnitude of dominant and nondominant extremity contribution to wheelchair propulsion. In the cross-slope condition the lower arm is exposed to greater propulsion demands in an effort to resist the downhill turning tendency. With 10 of 12 right-hand dominant subjects, it was therefore expected for the dominant limb, the lower limb on the cross-slope, to generate higher forces, power, and work compared with the nondominant limb. For the remaining conditions the timing characteristics, forces, work, and power were not consistently higher on either the dominant or nondominant limb. The absence of a consistent pattern of upper-extremity contribution to wheelchair propulsion limits the ability to predict injury in a specific limb based on asymmetry. Furthermore, investigators should be aware of variable side-to-side difference during wheelchair propulsion, which may influence interpretation when data are collected from a single limb or averaged for both limbs.

The magnitude of propulsion asymmetry was dependent, in part, on environment. The rationale for our hypothesis that symmetry indexes measured during community wheeling would be greater than those measured during laboratory conditions was based on differences in task demands. That is, reliance on 1 limb may become pronounced during more challenging propulsion conditions. Consistent with this hypothesis, the greater asymmetry identified during outdoor community conditions compared with the laboratory may be a reflection of the varied surface textures and surface inclinations encountered by subjects. It was therefore surprising that there were no differences in the magnitude of propulsion symmetry between indoor community and laboratory conditions. Both the ramp and the rolling resistance encountered with the low-pile carpet surface exposed subjects to more challenging propulsion conditions than either level tile or dynamometer tasks in the laboratory. Elucidation of factors contributing to or the absence of propulsion symmetry is unclear at this time. However, it is possible that fatigue may have been a factor during the outdoor condition. The outdoor tasks were components of a single, continuous course. In contrast, the indoor community and laboratory tasks were performed as discrete trials, with rest provided according to each subject's needs. Future studies that evaluate propulsion symmetry during fatigued and nonfatigued states may provide further insight to this question.

Laboratory, indoor, and outdoor community conditions were comprised of diverse tasks. The objective was to compare and contrast representative terrain surfaces for each condition. Ramps and side-slopes are routinely encountered during outdoor sidewalk wheeling. To have omitted these tasks would have been an incomplete evaluation of community propulsion demands. Furthermore, the side-slope section of the outdoor course was the only task that may have presented subjects with disparate upper extremity propulsion constraints: all other tasks had surfaces that were level in a mediolateral (relative to the wheelchair user) direction, and none of the tasks involved a change of direction. The side-slope was not, however, the only task that evoked an increase in propulsion asymmetry. Visual inspection of indexes for each task (see fig 1) indicates asymmetry was higher during almost all outdoor tasks compared with both indoor and laboratory conditions. Advantages to laboratory testing include between-center reproducibility and collection of kinematic and electromyography data. However, findings from the current study underscore the importance of evaluating propulsion in the user's natural environment.

This is the first known investigation of the symmetrical nature of wheelchair propulsion. From a statistical perspective, the results are profound. Asymmetry was identified for a comprehensive group of kinetic and temporal variables across a range of propulsion environments. The clinical impact of the results is less obvious. In almost all instances, the magnitude of the side-to-side differences for the group was small. Unfortunately, there are few studies that have investigated the propulsion biomechanics of injured subjects.[8-11] Furthermore, differences in methodology prohibit a comparison of results. Even with small differences in moments and forces, however, the cumulative difference between limbs may be significant in light of the repetitive nature of wheelchair propulsion. Future studies will be necessary to determine the role of asymmetry in the development of injury in this population. In the absence of contributing to injury, defining a range of asymmetry may be a useful clinical tool. When describing the upper and lower limits of ground reaction forces in a subject population without lower-extremity injury, Herzog et al[30] suggested the data may be useful as clinicians attempt to restore gait symmetry of an injured patient. Perhaps as knowledge of propulsion asymmetry expands, we may similarly use this information to guide rehabilitation of injured manual wheelchair users.

We have shown the impact of environment on upper-extremity asymmetry during wheelchair propulsion. There are, however, several additional factors that may have also contributed to asymmetry. It is possible there were subtle side-to-side differences in strength that were not identified during physical examination. Another potential contributing factor may be related to the manner in which subjects propelled their wheelchairs. Even though all tasks involved wheelchair propulsion in a straight direction, it is possible that subjects did not push their chair in a straightforward manner. Subjects may have alternately used one limb to steer the chair while the other limb provided a greater contribution to propulsion. Although the presence of upper-extremity asymmetry during manual wheelchair propulsion is multifactorial, determination of specific variables and their contribution to upper-extremity asymmetry beyond the wheeling environment is, unfortunately, beyond the scope of this investigation.

Study Limitations

There are limitations to this study. First, the investigation included a relatively small sample size. We were, however, still able to identify side-to-side differences in wheelchair propulsion within each task, and when comparing outdoor with laboratory conditions. It is possible differences between indoor and laboratory conditions may have been present with a larger cohort. Also, our cohort included subjects with variable level spinal cord lesions, and 1 subject with spina bifida. Using a diverse sample adds strength to the study, but the variability in measures may be secondary to the nonhomogeneous physical capacity of the participants. For example, a person with a lower lumbar spinal cord lesion may have poorer trunk control than someone with a mid-thoracic lesion. The impaired trunk stability may be a factor contributing to upper-extremity asymmetry. Future investigations that include larger sample sizes may permit comparison of symmetry across patient groups (eg, by lesion level or by pathology). Finally, the distance of each task was not constant. It is possible that the longer distance outdoor tasks may have fatigued the subjects, thus evoking propulsion asymmetry. Our push selection algorithm, however, identified the 3 consecutive pushes with the least variability for analysis. If fatigue played a meaningful role during outdoor propulsion, the strokes would have shown increasing variability. Therefore, the strokes with the least variability at the beginning of the task would have been selected for analysis. Furthermore, the different distances reflect the variable environmental demands: continuous outdoor propulsion distances are significantly greater than those encountered during indoor or laboratory propulsion.

CONCLUSIONS

Wheelchair propulsion asymmetry was identified in a cohort of experienced manual wheelchair users without upper-extremity pain or injury. Investigators should be aware that manual wheelchair propulsion is an asymmetrical act, which may influence interpretation when data are collected from a single limb or averaged for both limbs. The greater asymmetry identified during outdoor versus laboratory conditions emphasizes the need to evaluate wheelchair biomechanics in the user's natural environment. The clinical consequences of the asymmetry cannot, however, be determined by this investigation.

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List of Abbreviations

SCI spinal cord injury

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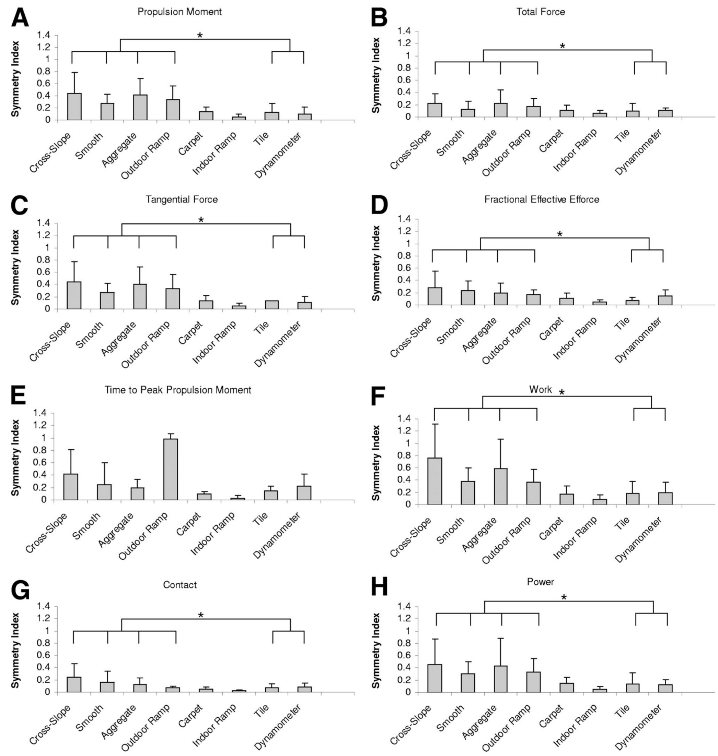

Fig 1.

Symmetry indexes for (A) propulsion moment, (B) total force, (C) tangential force, (D) fractional effective force, (E) time-to-peak propulsion moment, (F) work, (G) contact, (H) power. *Significant differences between laboratory and outdoor community conditions.

Table 1

Variable Calculation

Variable	**Calculation**
Average propulsion moment (M_z) (Nm)	Direct SmartWheel output
Average total force (F_{tot}) (N)	$\sqrt{\mathbf{F}_x^2 + \mathbf{F}_y^2 + \mathbf{F}_z^2}$
Average tangential force (F_{tan}) (N)	M_z/r
Average fractional effective force (N)	$\left(\mathbf{F}_{tan} * \mathbf{F}_{tot}^{-1}\right) * 100$
Time-to-peak propulsion moment (s)	M_z onset peak
Average work (J)	$\int M_z \, d\theta$
Length of push cycle (*s*)	M_z onset off
Instantaneous power (*W*)	$\omega * M_z$

Abbreviations: ω, angular velocity; $d\theta$, angular distance.

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Table 2

Within Condition Symmetry Indexes

Outdoor Terrain	Cross Slope			Smooth Concrete			Aggregate Concrete			Outdoor Ramp		
	D	ND	SI	D	ND	SI	D	ND	SI	D	ND	SI
M_z (Nm)	5.66±1.98	4.71±1.79	0.44±0.35	7.71±2.32	9.52±2.10	0.27±0.15	13.91±4.76	10.74±2.31	0.41±0.28	15.77±3.91	12.78±3.52	0.33±0.23
F_{tot} (N)	0.47±0.09	0.43±0.11	0.22±0.16	0.64±0.21	0.67±0.20	0.13±0.13	0.86±0.20	0.78±0.17	0.23±0.21	0.99±0.28	0.91±0.26	0.17±0.14
F_{tan} (N)	0.28±0.08	0.24±0.09	0.44±0.34	0.38±0.15	0.47±0.13	0.27±0.15	0.65±0.12	0.52±0.12	0.41±0.28	0.76±0.20	0.62±0.18	0.33±0.23
FEF (N)	61.00±13.96	58.19±13.30	0.28±0.27	59.33±14.46	69.42±10.71	0.24±0.16	74.43±11.75	65.95±10.30	0.20±0.16	74.97±14.89	65.56±12.62	0.17±0.08
Time peak (s)	0.12±0.04	0.11±0.04	0.42±0.39	0.20±0.09	0.20±0.06	0.25±0.35	0.24±0.06	0.22±0.06	0.20±0.13	0.29±0.60	0.28±0.08	0.10±0.09
Work (J)	7.98±3.87	6.16±2.90	0.76±0.56	11.89±5.07	15.79±5.04	0.38±0.23	23.28±8.48	16.94±4.68	0.59±0.48	26.55±8.76	21.17±7.22	0.36±0.22
Contact (s)	0.21±0.06	0.20±0.05	0.25±0.22	0.32±0.11	0.32±0.06	0.15±0.19	0.35±0.07	0.33±0.06	0.13±0.10	0.42±0.80	0.40±0.08	0.07±0.03
Power (W)	42.60±17.89	36.39±19.69	0.45±0.42	45.26±19.51	58.79±20.05	0.31±0.19	77.42±21.59	56.48±18.86	0.43±0.45	77.71±24.91	62.94±21.29	0.33±0.22

Indoor Terrain	Carpet			Indoor Ramp		
	D	ND	SI	D	ND	SI
M_z (Nm)	10.24±3.13	10.21±3.14	0.14±0.08	22.14±5.92	22.08±5.52	0.05±0.04
F_{tot} (N)	0.67±0.08	0.65±0.12	0.11±0.09	1.26±0.28	1.24±0.27	0.06±0.05
F_{tan} (N)	0.48±0.06	0.48±0.11	0.14±0.08	1.07±0.27	1.07±0.28	0.05±0.04
FEF (N)	69.47±8.14	72.45±12.06	0.11±0.08	83.06±20.32	84.72±20.12	0.05±.04
Time peak (s)	0.21±0.04	0.20±0.03	0.09±0.04	0.44±0.11	0.45±0.12	0.03±0.04
Work (J)	16.97±4.86	16.64±5.34	0.17±0.14	37.83±12.29	40.09±11.73	0.09±0.07
Contact (s)	0.34±0.06	0.33±0.06	0.05±0.04	0.57±0.15	0.57±0.14	0.02±0.01
Power (W)	60.59±17.88	61.24±22.48	0.14±0.10	90.93±39.81	90.47±38.71	0.05±0.04

Laboratory Terrain	Tile			Dynamometer		
	D	ND	SI	D	ND	SI
M_z (Nm)	6.80±2.20	6.97±2.48	0.13±0.15	6.21±2.32	6.27±2.26	0.10±0.11
F_{tot} (N)	0.51±0.10	0.50±0.12	0.10±.12	0.45±0.09	0.45±0.11	0.11±0.04
F_{tan} (N)	0.33±0.11	0.34±0.13	0.13±0.15	0.29±0.10	0.29±0.09	0.10±0.11
FEF (N)	63.50±14.76	65.99±14.58	0.07±0.05	63.48±18.29	63.72±15.69	0.15±0.10
Time peak (s)	0.20±0.06	0.19±0.05	0.14±0.08	0.20±0.08	0.21±0.06	0.22±.19

Laboratory Terrain	Tile			Dynamometer		
	D	ND	SI	D	ND	SI
Work (J)	10.91±4.49	10.55±4.46	0.18±0.20	9.78±4.56	9.89±4.91	0.20±0.17
Contact (s)	0.32±0.07	0.31±0.07	0.07±0.07	0.43±0.09	0.44±0.10	0.08±0.06‡
Power (W)	41.19±19.60	42.60±21.99	0.14±.18	27.06±13.29	28.14±15.06	0.12±0.09

NOTE. Values are mean ± SD.

Abbreviations: Contact, length of push cycle; D, dominant; FEF, average fractional effectiveness force; F_{tan}, average tangential force; F_{tot}, average total force; J, joule; M_z, average propulsion moment; ND, nondominant; SI, symmetry index; Time peak, time-to-peak propulsion moment; W, watt.

* *P*<.05;

† *P*<.001