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Mechanical efficiency of two commercial lever-propulsion mechanisms for manual wheelchair locomotion

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Abstract—The purpose of this study was to (1) evaluate the mechanical efficiency (ME) of two commercially available lever-propulsion mechanisms for wheelchairs and (2) compare the ME of lever propulsion with hand rim propulsion within the same wheelchair. Of the two mechanisms, one contained a torsion spring while the other used a roller clutch design. We hypothesized that the torsion spring mechanism would increase the ME of propulsion due to a passive recovery stroke enabled by the mechanism. Ten nondisabled male participants with no prior manual wheeling experience performed submaximal exercise tests using both lever-propulsion mechanisms and hand rim propulsion on two different wheelchairs. Cardiopulmonary parameters including oxygen uptake (VO_2), heart rate (HR), and energy expenditure (En) were determined. Total external power (P_{ext}) was measured using a drag test protocol. ME was determined by the ratio of P_{ext} to En. Results indicated no significant effect of lever-propulsion mechanism for all physiological measures tested. This suggests that the torsion spring did not result in a physiological benefit compared with the roller clutch mechanism. However, both lever-propulsion mechanisms showed decreased VO_2 and HR and increased ME (as a function of slope) compared with hand rim propulsion ($p < 0.001$). This indicates that both lever-propulsion mechanisms tested are more mechanically efficient than conventional hand rim propulsion, especially when slopes are encountered.

Key words: arm lever, cardiopulmonary strain, energy expenditure, lever-propelled wheelchair, lever propulsion, locomotion, mechanical efficiency, mobility aids, oxygen uptake, wheelchairs.

INTRODUCTION

Conventional wheelchairs are designed with hand rims for manual propulsion. However, hand rim propulsion is energetically inefficient, where the ratio of work to energy expenditure (En), or mechanical efficiency (ME), is often found to be less than 10 percent [1–5]. This is in contrast to walking, running, or cycling, which typically have an ME of 20 to 30 percent [6]. This may, in part, explain the relatively high cardiopulmonary requirements of typical wheelchair propulsion, including high metabolic cost, heart rate (HR), and oxygen uptake (VO_2) [2–4]. Along with an individual's disability, a limited physical work capacity may hinder active participation and rehabilitation efforts due to excessive fatigue or discomfort [7–8]. Physical inactivity and sedentary behaviors may further increase the risk of secondary complications related to cardiovascular disease in wheelchair users [9–10]. In order to improve ME and

Abbreviations: ANOVA = analysis of variance, En = energy expenditure, F_d = drag force, HR = heart rate, ME = mechanical efficiency, P_{ext} = external power, RER = respiratory exchange ratio, VE = minute ventilation, VO_2 = oxygen uptake.

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reduce the physical strain of wheelchair locomotion, optimization of the wheelchair-user interface to increase the effectiveness of power application has been studied [4,11]. These efforts have led to alternative wheelchair designs, including those that utilize push levers for propulsion rather than hand rims.

Lever-propelled wheelchairs are designed with manually operated push levers that transfer force to the wheels through a transmission mechanism. Despite conceptual similarities in operation, many different transmission styles exist for lever-propelled wheelchairs. Each mechanism attempts to improve functionality from both ergonomic and efficiency viewpoints. In general, previous studies that have compared lever propulsion with hand rim propulsion have shown that lever propulsion is superior in regard to ME [4–5,12–13]. Lever-propulsion mechanisms that have been tested in terms of physiological demand include friction and roller clutch systems [14]; the swing-turn gear system, which allows gear changes [15]; the MARC prototype, which allows for a constant mechanical advantage of the applied force [5]; the fixed crank-rod system, which drives the wheels directly [5]; and the three-wheeled synchronous lever-propelled chair [16]. However, the wheelchair designs tested in these studies were either early-stage prototypes, or to our knowledge, never made commercially available. Currently, at least two distinct lever-propulsion mechanisms are commercially available (**Figure 1**).

One such mechanism uses two independent manual push levers and a bidirectional roller clutch design that is contained within the wheel hub. The fixed 1:2 gear ratio results in an amplified torque output to the wheels when the levers are engaged.

The second mechanism available also uses two independent levers. However, rather than a bidirectional roller clutch, this design contains levers that are coupled to a spring mechanism, which is an assembly of belts and pulleys built onto the wheelchair frame. During the forward push phase of the lever stroke, torque is transmitted to the wheels through the belt and pulley mechanism while a torsion spring located in the pulley is tensioned. This spring provides a restoring torque that allows for a passive recovery phase following the forward stroke. The intent is to allow the levers to spring back without requiring the user to actively expend energy on pulling back and readying the levers for subsequent strokes.

Despite relatively widespread usage, neither of the two mechanisms described have been evaluated with respect to their operational energy costs and cardiopulmonary responses. Therefore, the primary purpose of our study was to quantify and compare the cardiopulmonary responses and ME of operating these two different lever-propulsion mechanisms. A secondary purpose of our study was to

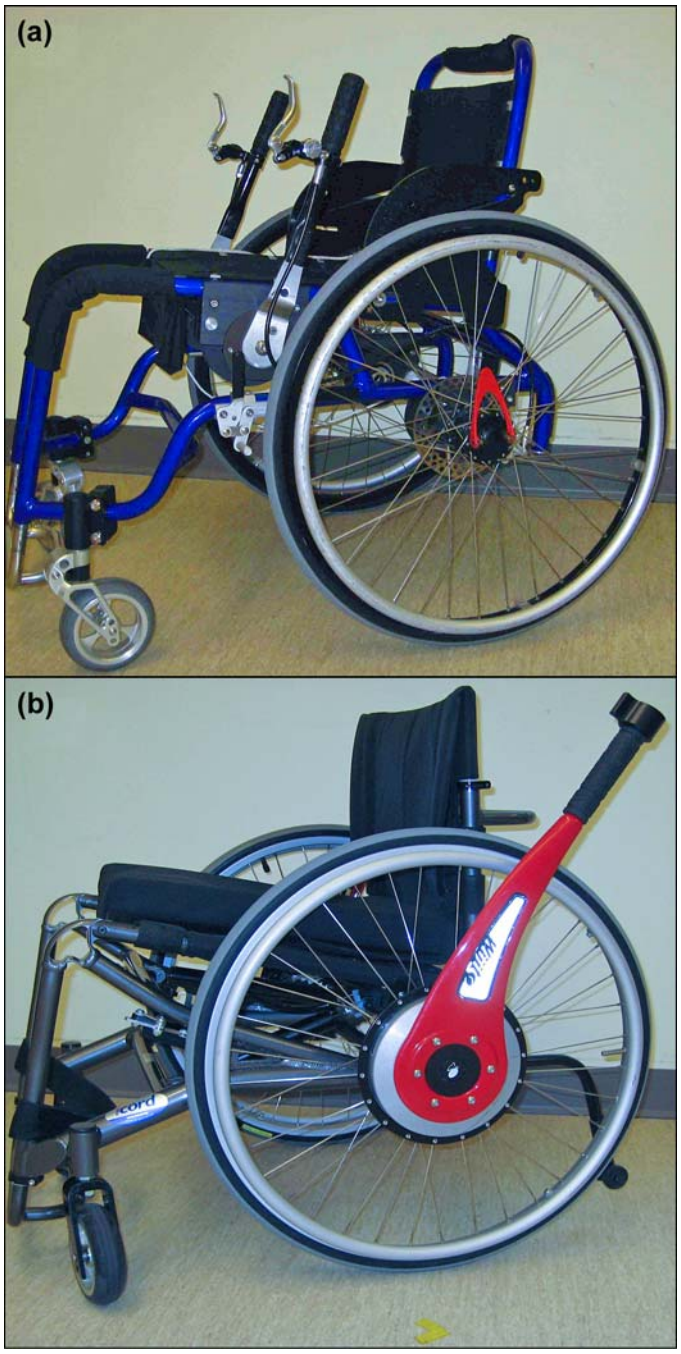

Figure 1.
(a) Willgo (spring) system (Willgo Ltd; Northampton, England).
(b) Wijit (roller) system (Superquad; Roseville, California).

confirm that lever propulsion is more efficient than hand rim propulsion. To this end, we compared the two lever-propulsion mechanisms with conventional hand rim propulsion. We hypothesized that lever-propulsion mechanisms designed with a torsion spring would be more mechanically efficient than mechanisms that use a roller clutch design and that hand rim propulsion, in general, would be less mechanically efficient than lever propulsion.

METHODS

Subjects

Ten nondisabled males (age: 23.5 ± 2.7 yr; mass: 80.6 ± 14.6 kg; height: 180.8 ± 6.5 cm) with no prior manual wheeling experience were recruited though word of mouth. Inclusion criteria for all participants included being healthy, aged 18 yr or older, and able to use a manual wheelchair without shoulder pain. Subjects were also required to fit comfortably into the available 16 or 17 in.-width wheelchairs. Individuals with muscular, cardiac, or respiratory illness were not permitted to participate in this study. The study received approval from the University of British Columbia's clinical research ethics board. All participants provided written informed consent prior to their participation in the study.

Wheelchairs

Two lever-propulsion systems were used for this study: a Wijit propulsion system (Superquad; Roseville, California) was used to test the bidirectional roller clutch mechanism, and a Willgo (Willgo Ltd; Northampton, England), which is a belt and pulley transmission with a torsion spring mechanism that enables users to have a passive recovery phase. The Wijit is a detachable system that can be customized to any standard wheelchair, whereas the Willgo comes fixed to its own wheelchair and is not meant to be detached. For both lever-propulsion systems, the levers can be disengaged to allow the option of using the hand rims for propulsion. **Table 1** summarizes the wheelchair characteristics.

A total of four different wheelchair conditions were tested: lever propulsion with the Wijit (roller-lever), lever propulsion with the Willgo (spring-lever), hand rim propulsion with the Wijit detached (roller-hand), and hand rim propulsion with the Willgo (spring-hand). For roller-lever, the Wijit was attached to a standard manual wheelchair (Instinct Mobility; Vancouver, Canada).

Procedure

Testing was partly based on a protocol outlined by van der Woude et al. [4]. Testing order of the four wheelchair conditions for each subject was randomized and spread across two different days (i.e., two conditions tested per

Table 1.
Wheelchair characteristics.

Characteristic	Willgo* (spring-lever/spring-hand)	Wijit† (roller-lever)	Standard‡ (roller-hand)*
Weight (kg)	17.8	18.7	12.9
Width (in.)	16	16	16
Wheelbase (cm)	52.5	41.5	41.5
Rear Wheel Diameter (cm)	61	61	61
Caster Diameter (cm)	12	12	12
Tire Pressure (psi)	110	110	110
Lever Length (cm)	30	50	—
Distance Between Levers (cm)	39	59	—
Stroke Angle (° max)	100°	75°	—
Mechanism	Torsion Spring	Roller Clutch	—
Gear Ratio (fixed)	1:1	1:2	—
Passive Recovery Phase	Yes	No	—
Detachable	No	Yes	—

*Willgo Ltd; Northampton, England.
†Superquad; Roseville, California.
‡Wijit propulsion system detached.
max = maximum.

day). During each visit, each subject performed a submaximal exercise test on a wheelchair treadmill (Max Mobility Inc; Nashville, Tennessee) with three discontinuous exercise stages while using a randomly assigned wheelchair condition. Each exercise stage was 4 min in length. Velocity remained constant at 0.97 m/s while incline was progressively increased for each stage (0° for stage 1, 1° for stage 2, and 2° for stage 3). Rest periods of up to 5 min were provided in between workloads and up to 30 min were provided between the two wheelchair conditions tested on each day. Prior to testing, subjects were given 15 min to wheel both on ground and on the treadmill to familiarize themselves with the assigned wheelchairs.

During testing, ventilator parameters and mixed expired gases were continuously collected with a TrueOne 2400 metabolic system (Parvo Medics; Sandy, Utah). The metabolic system was calibrated according to manufacturer's instructions prior to testing for each subject. VO_2, respiratory exchange ratio (RER), and minute ventilation (VE) were determined by averaging data from the last minute of each exercise stage, during which subjects were assumed to be at steady-state. HR was recorded using a portable telemetry system (Polar Electro Inc; Kempele, Finland). Rate of En was determined using standard thermal equivalents of oxygen based on VO_2 and RER values obtained during steady-state [17]. An RER of less than 1 was a requisite since the tests were submaximal.

The total external power (P_{ext}) was determined for each subject-wheelchair combination through a drag test procedure (**Figure 2**) [18]. Wheelchairs were connected (via a cable) to a force transducer (Omega Engineering Inc; Stamford, Connecticut) mounted onto the treadmill frame while subjects were instructed to sit passively in their assigned wheelchairs at a constant treadmill velocity [18]. The drag force (F_d) was measured with the force transducer at 10 levels of inclination between 0.35° and 3.00°. Linear regression analysis was used to determine F_d at 0° incline. P_{ext} was then determined for each exercise stage according to (**Equation (1)**)—

$$P_{ext} = F_d \times \nu, \quad \textbf{(1)}$$

where ν = treadmill velocity. Subsequently, gross ME was determined as (**Equation (2)**)—

$$ME = P_{ext}/En \times 100. \quad \textbf{(2)}$$

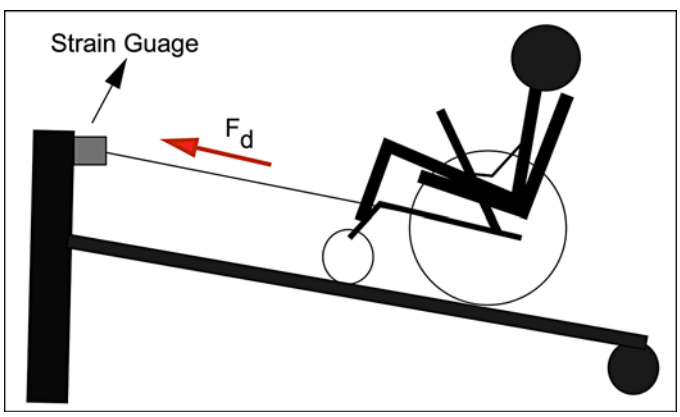

Figure 2.
Drag test setup showing wheelchair and subject on treadmill while force transducer measures drag force (F_d).

Statistical Analysis

To compare between the two lever-propulsion mechanisms, a 2 (lever-propulsion mechanism) × 3 (workload) repeated-measures analysis of variance (ANOVA) was used for each physiological measure between roller-lever and spring-lever. To assess the effects of lever versus hand rim propulsion, each lever-propulsion mechanism was compared with its respective hand rim propulsion condition. A 2 (propulsion type) × 3 (workload) repeated-measures ANOVA was applied to roller-lever versus roller-hand and to spring-lever versus spring-hand. All significant main effects were analyzed using pairwise comparisons, with a Bonferroni correction to control for type I error ($\alpha \leq 0.05$). All analyses were made using SPSS version 20 (IBM Corporation; Armonk, New York).

RESULTS

Roller-Lever Versus Spring-Lever

A repeated-measures ANOVA showed no significant effect of lever-propulsion mechanism for any of the measures, including ME, at all workloads. As expected, a significant effect of workload was found for all parameters ($p < 0.001$). As workload (or incline) increased, ME, VO_2, VE, RER, HR, and P_{ext} increased as well.

Lever Versus Hand Rim

Tables 2 and **3** shows results for all physiological measures for each lever-propulsion mechanism and its respective hand rim propulsion condition. **Figure 3**

Table 2.
Mean ± standard deviation of physiological measures for spring-lever and spring-hand.

Measure	0°		1°		2°	
	Spring-Lever	Spring-Hand	Spring-Lever	Spring-Hand	Spring-Lever	Spring-Hand
ME (%)	1.43 ± 0.38*	1.32 ± 0.37	8.48 ± 0.61*	7.11 ± 1.28	11.24 ± 0.97*	9.27 ± 1.00
VO_2 (mL/min/kg)	5.78 ± 0.66*	6.32 ± 0.73	7.63 ± 0.61*	9.42 ± 2.10	10.75 ± 0.97*	13.18 ± 1.35
HR (bpm)	81.28 ± 8.63*	86.15 ± 9.02	93.30 ± 10.51*	98.50 ± 13.62	107.52 ± 10.27*	116.11 ± 14.61
P_{ext} (W)	2.24 ± 0.65	2.24 ± 0.65	18.08 ± 2.97	18.08 ± 2.97	33.94 ± 5.64	33.94 ± 5.64
RER	0.89 ± 0.07	0.87 ± 0.09	0.97 ± 0.03	0.96 ± 0.05	0.99 ± 0.007	0.96 ± 0.06
VE (L/min)	16.49 ± 5.76	16.33 ± 5.76	20.29 ± 5.23	24.69 ± 8.93	29.68 ± 9.19	29.90 ± 9.84

*Significantly different from spring-hand at respective workload ($p < 0.001$).
bpm = beats per minute, HR = heart rate, ME = mechanical efficiency, P_{ext} = external power, RER = respiratory exchange ratio, VE = minute ventilation, VO_2 = oxygen uptake.

Table 3.
Mean ± standard deviation of physiological measures for roller-lever and roller-hand.

Measure	0°		1°		2°	
	Roller-Lever	Roller-Hand	Roller-Lever	Roller-Hand	Roller-Lever	Roller-Hand
ME (%)	1.12 ± 1.12	1.11 ± 0.27	8.48 ± 1.52*	7.44 ± 0.90	10.96 ± 1.62*	9.32 ± 1.26
VO_2 (mL/min/kg)	5.91 ± 0.86	6.34 ± 0.86	8.09 ± 1.40*	8.55 ± 1.07	11.58 ± 1.63*	12.72 ± 1.80
HR (bpm)	81.91 ± 11.78*	85.39 ± 10.72	90.63 ± 15.82*	93.45 ± 16.08	104.88 ± 12.54*	112.46 ± 13.25
P_{ext} (W)	1.88 ± 0.46*	1.75 ± 0.43	18.3 ± 2.64*	17.25 ± 2.50	34.93 ± 5.23*	32.61 ± 4.77
RER	0.90 ± 0.08	0.87 ± 0.09	0.89 ± 0.08	0.89 ± 0.06	0.94 ± 0.05	0.96 ± 0.04
VE (L/min)	18.02 ± 5.16	17.76 ± 4.30	22.21 ± 7.69	23.46 ± 7.59	31.38 ± 16.70	32.79 ± 12.28

*Significantly different from roller-hand at indicated workload ($p < 0.001$).
bpm = beats per minute, HR = heart rate, ME = mechanical efficiency, P_{ext} = external power, RER = respiratory exchange ratio, VE = minute ventilation, VO_2 = oxygen uptake.

shows changes in ME between each lever-propulsion mechanism and its respective hand rim propulsion condition. For spring-lever versus spring-hand, a significant main effect of propulsion type was found for ME, VO_2, and HR (**Figure 4**). Pairwise comparisons indicated significant differences at all three workloads ($p < 0.001$). As expected, there was no difference in P_{ext} between spring-hand and spring-lever since the wheelchair and F_d remained the same between the two conditions.

For roller-lever versus roller-hand, a significant main effect of propulsion type was found for ME, VO_2, HR, and P_{ext} (**Figure 4**). Pairwise comparisons for ME and VO_2 indicated significance at the second and third workloads ($p < 0.001$). Pairwise comparisons for HR were significant at all workloads ($p < 0.001$). As expected, a significant difference in P_{ext} was observed between roller-lever and roller-hand since the detachment of the levers resulted in a lighter chair and therefore a different F_d.

DISCUSSION

The primary aim of our study was to compare two commercially available lever-propulsion mechanisms with respect to cardiorespiratory parameters. A secondary objective was to confirm previous findings that lever propulsion is more efficient than conventional hand rim propulsion. Previous studies have generally shown that, compared with hand rim propulsion, lever propulsion is associated with a reduced cardiopulmonary response and operational energy cost for a given workload and therefore a higher ME [4–5,13,15]. However, based on previous reports, the improved ME observed with lever propulsion is wheelchair-specific and dependent on the exact conditions (incline, speed) in which the wheelchair is propelled. For example, using a similar subject group and exercise protocol as our study, van der Woude et al. tested a lever-propelled wheelchair and

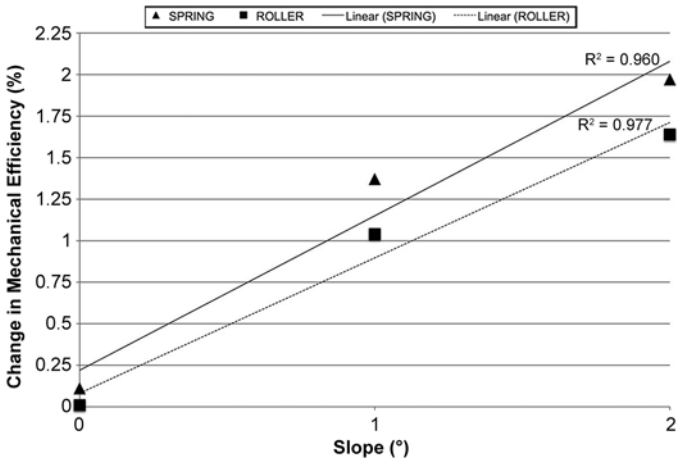

Figure 3.
Change in mechanical efficiency between lever and hand rim propulsion versus slope.

found it to be more mechanically efficient than hand rim propulsion on all levels of incline between 0° and 2.5° [5]. It has also been reported that some lever-propelled wheelchairs are more mechanically efficient than hand rim propulsion but only on inclines greater than 2° [4].

The results from the current study are comparable with both of these previous findings. We found that roller-lever did not show an advantage in ME compared with its respective hand rim propulsion condition until the second and third workloads, which corresponded to 1° and 2°, respectively. However, spring-lever was found to be more mechanically efficient than hand rim propulsion on all levels of incline tested (0°–2°). Despite a constant P_{ext} between spring-lever and spring-hand (due to the inability to detach the lever mechanism), switching to lever propulsion from hand rim propulsion resulted in a lower VO_2 and En and therefore a higher ME.

Figure 3 shows that increases in ME during lever propulsion are a function of slope. This relationship is in agreement with previous studies on wheelchair propulsion [3–4,16,19]. It can be attributed to a decrease in the relative contribution of resting metabolic rate to the overall En at a given workload [20–21]. If this relationship is extended to the slope of a standard wheelchair ramp of 4° to 5°, the apparent benefits of lever propulsion may be even more significant. Therefore, when considering the benefits in ME of lever propulsion, the propulsion environments of users must also be taken into account.

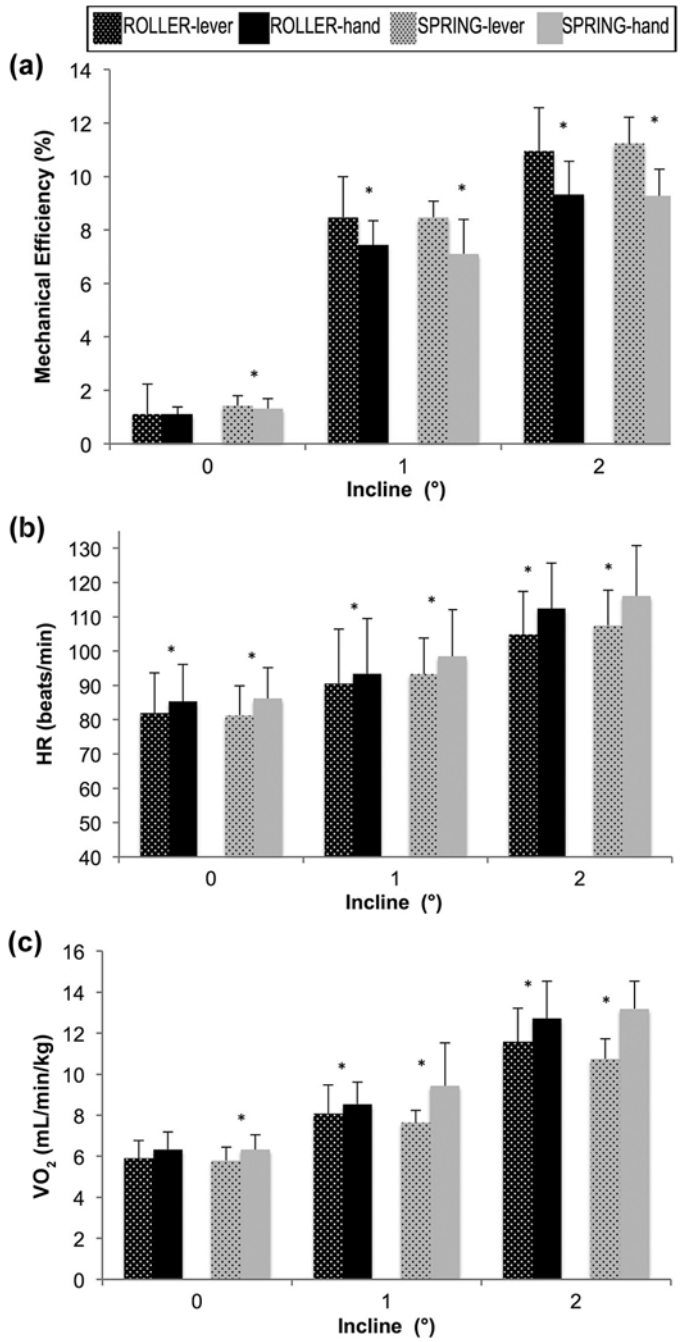

Figure 4.
Mean ± standard deviation (n = 10) of **(a)** mechanical efficiency, **(b)** heart rate (HR), and **(c)** oxygen uptake (VO_2) for lever propulsion and hand rim propulsion at each workload. *Significant difference (p < 0.001).

With respect to the comparison between the two lever-propulsion mechanisms tested, we hypothesized that a spring mechanism, such as the one tested in spring-lever,

would increase the ME of propulsion due to a passive recovery phase following a forward stroke. However, we found no significant differences in ME or in any of the other physiological measures compared with the roller clutch mechanism, which lacked such a passive recovery phase in operation. Therefore, mechanical differences between the torsion spring mechanism and roller clutch mechanism do not appear to translate into significant differences in ME or in any other of the physiological responses tested.

It is important to recognize that cardiopulmonary responses of wheelchair propulsion represent only one aspect of wheelchair evaluation. Other factors to consider may include biomechanical aspects such as joint kinetics and propulsion mechanics, functionality, comfort, adjustability, and maneuverability (steering). Rifai Sarraj et al., for example, created a questionnaire to assess user satisfaction of lever-propelled wheelchairs, taking into account items such as comfort, safety, aesthetics, portability, etc. [22]. The torsion spring mechanism used in this study, for instance, is designed with a belt transmission that prohibits backward propulsion with the levers. This sacrifices a degree of maneuverability and convenience because users must disengage the lever mechanism and use the hand rims in order to propel the wheelchair backward. The bidirectional roller clutch design, on the other hand, allows users to propel the wheelchair with the levers either forward or backward by shifting the transmission via the lever handles. In addition, the torsion spring mechanism is fixed to the chair, whereas the roller clutch mechanism tested can be fitted to the majority of wheelchairs, allowing for greater customizability and comfort. Another important distinction between the two lever-propulsion mechanisms tested in this study relates to the positioning of the transmission systems. The roller clutch mechanism contains an "outboard" transmission that is entirely contained within the wheel hub. This increases portability and protects the system from the elements but also increases the wheelchair width and horizontal distance between the levers. Levers that are farther apart can increase shoulder abduction and may limit elbow extension. The torsion spring mechanism, on the other hand, uses an "inboard" transmission, which has the advantage of keeping the levers closer together and thus allowing users to retain a more natural positioning of the shoulder during propulsion. Subjective feedback from our study participants generally indicated a preference for this positioning. This may be an important consideration in minimizing shoulder strain, because overuse injuries to the upper limbs associated with hand rim propulsion are well documented [23–24]. It has been suggested that the neutral positioning of the upper limbs during lever propulsion may redistribute the forces acting on the glenohumeral joint and therefore potentially lower the long-term risk of overuse injuries to the upper limbs [25]. Future investigations should include such biomechanical evaluations for each lever-propulsion mechanism. The characterization of joint kinematics or contact force could potentially allow for further comparison of these lever-propulsion mechanisms.

LIMITATIONS

In our study, we used nondisabled individuals as research subjects. This allowed us to limit the influence of motor experience on physical capacity and ME [26–28]. It is important to consider that biomechanical and physiological differences in wheelchair propulsion do exist between nondisabled participants and habitual wheelchair users [26]. However, previous studies have demonstrated that the physiological responses of nondisabled and habitual wheelchair users respond similarly to variations in workload, propulsion technique, and wheelchair models [4,13,29]. Therefore, although absolute differences in physiological parameters between nondisabled and wheelchair-dependent users may exist, the relative responses to the lever-propulsion systems may be similar, and therefore, data from our study may be of value to the habitual wheelchair user.

Finally, the measurement of ME in our study was confined to locomotion in a continuous straight line. Real life wheelchair propulsion involves maneuvering beyond a straight line, and steering likely affects the physical strain of wheelchair propulsion [30].

CONCLUSIONS

Based on the results of our study, we found no differences in ME between the two commercially available wheelchair lever-propulsion mechanisms tested. Despite a passive recovery phase, lever propulsion with the torsion spring mechanism showed no increase in ME compared with the lever propulsion with the roller clutch design. However, while no relative advantage was observed between the two mechanisms, both lever-propulsion mechanisms tested showed improvements in ME compared with conventional hand rim propulsion, especially when

slopes are encountered. Therefore, lever propulsion in general may be a viable consideration for wheelchair users hoping to increase the ME of manual wheelchair locomotion. In comparing these lever-propulsion mechanisms, factors other than cardiopulmonary parameters may be important considerations in future studies. Further work in evaluating the wheelchair-user interface may help to optimize future designs.

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Institutional Review: All participants in the study signed a written informed consent. The study was reviewed and approved by the Clinical Research Ethics Board at the University of British Columbia.
Participant Follow-Up: The authors plan to inform participants of the publication of this study through the research information center.

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