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Kinetic and physiological analysis of the GAME^{Wheels} system

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Abstract—For individuals with a spinal cord injury or dysfunction (SCI/D), opportunities to exercise are limited and are usually not highly motivating experiences. Exercise programs or extracurricular activities may help increase or maintain the cardiovascular fitness level of individuals with SCI/D. The GAME^{Wheels} system, an interface between a portable roller system and a computer, enables an individual to control a video game by propelling his or her wheelchair. The purpose of this study was to investigate whether the propulsive forces used during video play, both with and without the GAME^{Wheels} system, were different. A secondary purpose was to examine differences in metabolic parameters during exercise under these two conditions. Ten manual wheelchair users exercised on the GAME^{Wheels} system with and without controlling a video game. Physiological and kinetic data were collected six times during two exercise trials. Kinetic data were recorded with the SMART^{Wheel} and used to investigate propulsion forces. No significant differences were found in the resultant force, rate of rise, or number of hand contacts with the pushrims. This study showed that propulsion pattern did not change significantly when wheelchair users exercised while playing a computer video game. Oxygen consumption, ventilation, and heart rate were significantly different ($p < 0.05$) between the two groups during the last three exercise intervals and cooldown. Playing a video game while exercising may help to motivate manual wheelchair users to exercise longer and regularly, something that was reported by this study's subjects; likewise, exercising while playing a video game may not be associated with higher pushrim forces and stroke frequencies.

Key words: *cardiovascular fitness, computer games, exercise, wheelchair.*

INTRODUCTION

Wheelchair users with spinal cord injury or dysfunction (SCI/D) tend to decrease their activity levels after their injury [1–7], which can lead to an increased incidence of cardiovascular disease. Participating in exercise may be problematic for individuals who use manual wheelchairs. The lack of exercise and/or sedentary lifestyle of many manual wheelchair users may lead to weight gain, increasing the possibility of cardiovascular diseases. Some research has shown that the activities of

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daily living (ADL) do not help improve or even maintain manual wheelchair users' cardiovascular fitness level [2,6,7]. Some ADL involves moderate to high levels of exertion but for only a short time. The heart rate (HR) and oxygen consumption may become elevated, but they are not sustained for an adequate amount of time to attain any cardiovascular benefits [8].

Methods have been developed that examine the forces imparted during manual wheelchair propulsion [9,10]. The SMART^{Wheel} is an eight-channel, specialized wheelchair wheel that allows for collection of propulsion forces applied to the pushrim [9]. Researchers have used SMART^{Wheel}s to investigate the forces and moments applied to the pushrims during propulsion at the starting point of propelling the wheelchair and at different propulsion speeds [9,11–13]. These studies have shown that large impact spikes and/or the speed at which the hand impacts the pushrim may be factors related to secondary injuries [11–13]. In addition, body weight and stroke frequencies have been correlated to carpal tunnel syndrome [11].

As with the general population, maintaining cardiovascular fitness for manual wheelchair users is important. Unfortunately, manual wheelchair users may encounter barriers in their efforts to exercise. These barriers may include inaccessible locations and outdated equipment. Unlike the advances made in the general population's exercise equipment, limited exercise resources exist for individuals with disabilities. Fortunately, the GAME^{Wheels} is one resource for manual wheelchair users. GAME^{Wheels} has been designed to interface between one's computer and a wheelchair dynamometer. One can play a computer game by propelling the wheelchair. Subjects tested previously reported being so involved with playing the video game that they forgot they were exercising [14,15].

During an initial study of the GAME^{Wheels} system, individuals would shorten their recovery phase in order to keep their hands close to the pushrim to better control the racecar [14]. A shorter backswing (recovery phase) in the propulsion pattern would mean less time to develop hand speed and possibly decrease the impact spike. Because the GAME^{Wheels} system was designed to allow any computer game to be used, the propulsion stroke may be altered in different ways, depending on the video game that the wheelchair user chooses to play. The video game used for this study was a racecar game; the individuals had to control the racecar counterclockwise around an oval racetrack. Possibly, the wheelchair user does not realize the changes in propulsion that he or she is doing or the changes in forces that he or she is applying to the pushrim. A larger impact spike and/or shorter time of hand contact might lead to higher frequency of hand contacts during exercise with the video game play and therefore may lead to a secondary injury. If this were the case, manual wheelchair users would need to be aware that using the video game may alter their propulsion stroke and lead to a secondary injury.

The purpose of this study was to ascertain the forces imparted on manual wheelchair users when playing a video game by propulsion, as well as to determine differences in metabolic parameters with and without game play. Researchers hypothesized that no significant differences existed for the propulsive forces applied to the pushrim and stroke cadence while wheelchair users exercised with or without the video game. Researchers also hypothesized that wheelchair users' metabolic work rate would be higher while exercising with the game compared to exercising without the video game (verifying previous work).

METHODS

Subjects

Ten subjects were recruited from the previous study on the GAME^{Wheels} system based on availability [15]. The subjects had a mean age of 38.7 ± 8.0 years and were 17.6 ± 12.2 years postdiagnosis. Injuries included two injuries at T10 or below, six injuries between T3 to T9, three injuries at T4 to T3, one injury at C6 to C7 level, and one person with multiple sclerosis. All subjects used manual wheelchairs as their primary means of mobility. Because we were interested in examining propulsive forces, all subjects were used in the analyses. Fifty percent of the sample was male. All subjects gave written informed consent before being tested at the Human Engineering Research Laboratories (HERL). All subjects had similar experience playing the racecar game using their wheelchair with the GAME^{Wheels} system.

Instrumentation

Each subject's wheelchair was bilaterally fitted with SMART^{Wheel}s [9]. Each SMART^{Wheel} was connected to a computer for collection of bilateral kinetic data. The SMART^{Wheel} is an instrumented three-beam design "mag" wheel (three wide plastic spokes) with a precision of 2 N and a resolution of 0.2 N, at a data collection rate of 240 Hz [9]. (See **Figure**.)

Figure.
Instrumentation of SMART^Wheel can be seen. A SMART^Wheel is mounted to both sides of wheelchair. Wires extending out in front of rollers are connected between Game^Wheels system and computer. Wires connecting SMART^Wheel to laptop computers extend out on opposite side of camera view.

Protocol

The protocol was the same as the previous study by O'Connor et al. with the GAME^Wheels system used to exercise with and without playing a video game [15]. However, during this protocol, each subject's personal wheelchair wheels were replaced by SMART^Wheels. Subjects participated in both exercise trials, with the order of testing randomized between with and without the video game. Subjects were assisted onto the GAME^Wheels system. The SMART^Wheels were aligned for calibration [9]. All subjects were given 10 to 15 min to refamiliarize themselves with the GAME^Wheels system, and general reminders were given about its use. The trial started when the subjects' HRs had returned to their resting HRs, prior to the trial period of game play.

Each exercise trial started with a 2 min "warm-up" session, followed by a 20 s break in propulsion in order to start the video game. The 20 s break was repeated for both testing periods to match trials. For the trial using the video game, the racecar game was started. In both trials, the wheelchair users were instructed to start propelling at the end of the 20 s, even if the video game had not yet started. The wheelchair users propelled with or without the video game for 16 min of exercise, with 2 min of warm-up and 2 min of cooldown, for a testing time of 20 min total. At the end of the 16 min, the individuals were instructed to propel comfortably to cool down. The video game ran during the 2 min of cooldown. Subjects were given at least a 2 hr break between exercise trials.

Collection of Biomechanical Data

The SMART^Wheels were used to collect pushrim kinetic data investigating whether exercising with the video game might alter an individual's propulsion pattern. Kinetic data (forces and moments about the pushrim) were collected for 10 s at six intervals, including the last 10 s of warm-up and cooldown (2 min intervals) and each of the four 4 min exercise intervals (6, 10, 14, and 18 min intervals). Previous research has shown that 10 s is adequate to assess the amount of propulsive forces (reproducibility of strokes) and also provides at least three strokes to achieve an average value [12]. During the force data collection, subjects were instructed to try to maintain their propulsion patterns, despite the game, allowing for several propulsion strokes. This allowed the hands to contact the pushrim several times. Because the video game used an oval track (i.e., more than 50 percent of the time they were going straight), the subjects were likely to be on a straight section when data were collected.

Collection of Metabolic Data

This study took place within a few months of the previous study using the GAME^Wheels system; therefore, we used the submaximal testing data (VO_2/kg) from the first study as guidelines [15]. A SensorMedics Metabolic Cart* was used to collect physiological data. Prior to data collection, the cart was prepared following directions in the manual, and calibration was checked. If necessary, the cart was recalibrated according to the manual specifications [16]. Physiological data were collected for these sets of trials, because this is preferred over estimates based on previously collected data. For both exercise trials, a Polar† HR monitor was placed on the subject's

*SensorMedics Model 2900, 22705 Savi Ranch Parkway, Yorba Linda, CA 92887.

†Polar Instruments Inc., 320 E. Beelevue Ave., San Mateo, CA 94401.

chest under the clothing and secured with an elastic strap. Two wristwatch monitors that displayed the subjects' HR were used for feedback. One monitor was placed in visual site on the table for the subjects to monitor their own HRs, and one was put on the back of the wheelchair for the tester to record HRs. With the use of established procedures, a maximum and minimum arm-work HR was calculated; the minimum HR, which was equal to 60 percent of the maximum HR, was used for the training zone [8,17]. Before each test trial, subjects were instructed to maintain their HR above their own minimum, calculated, training zone level. The individuals monitored their HR during exercise to stay within their training zone for both trials. The wheelchair users were instructed to keep their HRs above their minimum level during both exercise bouts. Subjects confirmed that they had not eaten in 2 hours preceding the trials. The video game was set so that the game would not end if the racecar drivers (wheelchair users) crashed. If the subjects crashed, they had to propel more to get free from the wall. At the beginning of each exercise trial, physiological data (HR, ventilation rate [V_E], and oxygen consumption per body weight [VO_2/kg]) collections were started and collected for the entire testing time.

Data Reduction

MATLAB[*] programs were used for the kinetic data calculations. This study concentrated on the forces applied to the pushrim during exercise, with six different time points of data collection. The six time points corresponded to four during activity, one during warm-up, and one during cooldown. The first three strokes during the 10 s data collection period were averaged for each of the six time points. Because of the possibility of different forces applied to the left and right pushrims because of the oval track, the forces were combined and averaged to achieve an overall force. The rate of rise was calculated with the use of the first three strokes during each of the four time periods within the exercise interval. The maximum value was found for each rate of rise, and those three maximum values were averaged for each of the exercise trials for each side. The resultant force (FR) was the total force applied to the pushrim and was calculated with the tangential force (Ft), radial force (Fr), and medial-lateral force (Fz). A peak force for the three strokes was calculated and averaged. Note that the forces measured during the video game play may be increased because of crashing into virtual walls and the other racecars. The physiological data were divided into six data collection times for analyses, which corresponded to the six kinetic data collection time points.

Statistical Analysis

Data were examined and found to be normally distributed; therefore, parametric statistics were used. Analyses were completed with the use of SPSS[†] and SAS software. The alpha level was set at 0.05 and was not adjusted to accommodate for multiple comparisons. Paired t-tests were used to compare factors (i.e., HR, ventilation), with and without the video game. Mixed models were used to ascertain if overall differences existed between the two conditions. Different mixed models were developed for the several outcomes (i.e., rate of rise, ventilation). Mixed modeling was used as the same subjects participated in both conditions. This type of modeling allows for both random and fixed effects. The fixed and random effects entered into each model included the 10 individuals, left and right sides, with and without the GAME^{Wheels} system, and the four data collection time points during exercise.

RESULTS

Biomechanical Data

The biomechanical variables that were examined included the number of hand contacts with the pushrim, hand contact duration with the pushrim, maximum resultant force, and maximum resultant force rate of rise. The mixed model showed no statistical differences between exercise with or without the video game for the number of hand contacts with the pushrim during the four SMART^{Wheel} data collection intervals. Although not significant, the number of hand contacts with the pushrim during the first period was higher for the group and was trending toward showing a statistical difference with $p = 0.083$. Further statistical analyses showed that the number of hand contacts for the five male subjects was statistically higher during the second time interval of exercise ($p = 0.019$)

[*]The MathWorks, Inc., 24 Prime Park Way, Natick, MA 01760–1500.

[†]SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606–6307.

and that no statistical differences existed between exercise with and without the video game play for the other three exercise time intervals.

The number of hand contacts to the pushrim showed no significant differences between left and right sides during exercise with ($p = 0.320$) and without ($p = 0.930$) the Game^{Wheels} system. Exercise data with the video game positioned on the left side were compared to data without the video game on the left side, and no significant differences ($p = 0.102$) were found. This comparison was also done on the right side, which was trending toward being significantly different at $p = 0.073$. Most of the individuals (90 percent) had a different number of strokes for each of the four data collection intervals during exercise with and without video game play. The difference in the number of strokes between exercise with and without the video game play ranged from zero to three strokes (**Table 1**). However, the propulsion stroke comparing left and right sides for all exercise bouts showed a difference of zero or one stroke (**Table 2**).

Table 1.
Comparison of average number of hand contacts (strokes) with pushrim, during exercise for subjects with and without video game.

ID No.	GAME^{Wheels} (SD)	No GAME^{Wheels} (SD)
1	5.0 (0.00)	3.0 (0.00)
2	8.3 (0.89)	8.9 (1.55)
3	7.6 (1.06)	7.3 (0.46)
4	6.9 (0.64)	7.0 (0.76)
5	7.9 (0.83)	6.9 (0.83)
6	7.0 (0.00)	8.1 (0.83)
7	6.5 (0.53)	5.3 (0.46)
8	7.5 (0.93)	6.3 (1.16)
9	5.8 (0.46)	3.1 (0.35)
10	9.0 (0.00)	9.0 (0.00)

Table 2.
Number of hand contacts with pushrim during exercise. Trials B to E refer to first, second, third, and fourth exercise intervals.

Ex Trial	gw L (SD)	ngw L (SD)	gw R (SD)	ngw R (SD)
B	7.4 (1.4)	6.0 (1.8)	7.2 (1.4)	6.1 (1.9)
C	6.9 (1.4)	6.6 (2.4)	7.0 (1.3)	6.6 (2.3)
D	7.4 (1.3)	6.4 (2.4)	7.3 (1.3)	6.3 (2.3)
E	6.9 (1.2)	6.9 (2.4)	7.0 (1.2)	6.9 (2.4)

gw = with video
ngw = without video
L = left
R = right
Ex = exercise

The average number of strokes during the 10 s of exercise data collected for the 10 subjects is stated in **Table 3**. The data are further divided into male and female side comparisons during exercise with and without using the GAME^{Wheels} system. A significant difference was found in the time the hand was in contact with the pushrim between the exercise trials with and without use of the GAME^{Wheels} system for the five males ($p = 0.010$) and five females ($p = 0.014$) (**Table 3**). The females were on the pushrim for a significantly longer time than the males during the exercise trial without the GAME^{Wheels} system ($p = 0.001$).

No statistical differences were documented for maximum or peak forces calculated from the first three strokes during any of the four 4 min data collection points for the entire group or gender subgroups (**Table 4**). The rate of rise or the impact spike was not statistically different ($p < 0.05$) for the 10 subjects in this study.

Physiological Data

Analyses of the three physiological variables VO_2/kg, V_E, and HR) showed significant differences between exercise with the GAME^{Wheels} system and without the system during the second, third, and fourth time intervals of exercise and during cooldown. Oxygen consumption per body weight data is presented in **Table 5**, ventilation rate data are presented in **Table 6**, and HR data are presented in **Table 7**. The mixed model yielded no significant differences overall. As can be seen, subjects had higher oxygen consumption, higher ventilation rate, and higher HR for all intervals after warm-up when exercising with the GAME^{Wheels} system. These differences were significant for all physiological variables during the last three exercise intervals and during cooldown.

DISCUSSION

This study compared differences of propulsive forces used during video play both with and without the GAME^{Wheels} system. When the forces were examined, the number of hand contacts with the pushrim was measured. Results indicated that when the subject's right side during game play was compared to the subject's right side without game play, a trend toward a significant difference ($p = 0.07$) emerged. This may be a result of the counterclockwise track that the subjects used to race. Consequently, subjects may have propelled more with the right

Table 3.
Average hand contact time (s) with pushrim for males/females during exercise intervals legend. Trials B to E refer to first, second, third, and fourth exercise intervals.

Trials ($p < 0.05$)	GAME[Wheels] ($p = 0.922$)		No GAME[Wheels] ($p = 0.007$)*		Female ($p = 0.003$)*		Male ($p = 0.145$)	
	Female (SD)	Male (SD)	Female (SD)	Male (SD)	GAME[Wheels] (SD)	No GAME[Wheels] (SD)	GAME[Wheels] (SD)	No GAME[Wheels] (SD)
B	0.64 (0.10)	0.57 (0.24)	0.82 (0.32)	0.67 (0.12)	0.64 (0.10)	0.82 (0.32)	0.57 (0.24)	0.67 (0.12)
C	0.63 (0.12)	0.63 (0.11)	0.83 (0.31)	0.64 (0.14)	0.63 (0.12)	0.83 (0.31)	0.63 (0.11)	0.64 (0.14)
D	0.58 (0.09)	0.61 (0.13)	0.82 (0.33)	0.64 (0.10)	0.58 (0.09)	0.82 (0.33)	0.61 (0.13)	0.64 (0.10)
E	0.61 (0.07)	0.64 (0.09)	0.75 (0.30)	0.66 (0.10)	0.61 (0.07)	0.75 (0.30)	0.64 (0.09)	0.66 (0.10)

*Significant differences.

Table 4.
Averaged max resultant force (N) and max resultant force rate of rise (N/s) for four exercise intervals with and without video game. Trials B to E refer to first, second, third, and fourth exercise intervals.

Trials	Max Resultant Force (N)			Rate of Rise (N/s)		
	GAME[Wheels]	No GAME[Wheels] (SD)	*p* Value (SD)	GAME[Wheels]	No GAME[Wheels] (SD)	*p* Value (SD)
B	60.659 (17.4)	57.572 (10.5)	0.401	1076.534 (448.0)	833.074 (334.3)	0.097
C	61.625 (14.6)	61.692 (24.3)	0.989	908.896 (291.7)	1018.676 (486.3)	0.260
D	61.677 (13.1)	62.617 (19.9)	0.825	951.312 (331.1)	924.398 (378.9)	0.720
E	62.251 (17.9)	59.047 (16.3)	0.506	865.946 (289.6)	948.216 (448.1)	0.585

Table 5.
Significant differences ($p < 0.05$) for oxygen consumption (mL/kg/min). Trial A refers to warm-up interval; Trials B to E refer to first, second, third, and fourth exercise intervals; and Trial F refers to cooldown interval.

Trials	VO^2/kg Mean Averages		
	GAME[Wheels] (SD)	No GAME[Wheels] (SD)	*p* Value
A	7.424 (1.64)	7.851 (2.17)	0.420
B	11.039 (2.76)	10.394 (2.58)	0.239
C	11.865 (2.92)	10.048 (2.76)	0.002*
D	11.798 (3.42)	9.746 (2.59)	0.005*
E	11.755 (3.21)	9.292 (2.56)	0.002*
F	9.826 (2.20)	7.614 (1.99)	0.002*

*Significant differences.

Table 6.
Significant differences ($p < 0.05$) for ventilation rate (b/min). Trial A refers to warm-up interval; Trials B to E refer to first, second, third, and fourth exercise intervals; and Trial F refers to cooldown interval.

Trials	Ventilation Rate Mean Averages		
	GAME[Wheels] (SD)	No GAME[Wheels] (SD)	*p* Value
A	21.358 (7.8)	22.812 (10.26)	0.168
B	31.058 (14.60)	28.826 (10.81)	0.307
C	34.652 (14.74)	27.690 (11.25)	0.003*
D	35.463 (17.82)	26.496 (10.46)	0.012*
E	35.076 (18.13)	25.053 (9.22)	0.016*
F	29.059 (13.08)	21.030 (7.93)	0.012*

*Significant differences.

side to turn the racecar left. Mulroy et al.'s study of muscle activity in the shoulder during wheelchair propulsion reported a cadence of 67 cycles a minute [18]. The results from this study show a cadence of 50 to 90 strokes a minute while subjects exercised with the video game and show a cadence of 30 to 90 strokes a minute without the video. Analyzing the time the hand is in contact with the pushrim shows that the females stayed on the pushrim longer than the males during exercise without the video. To control the car, the individuals kept their hands on the pushrims longer. This longer hand contact shortened the recovery phase and reduced the impact spike delivered to

Table 7.
Significant differences ($p < 0.05$) for HR (b/min). Given are averaged maximum resultant forces in newtons and averaged resultant force rate of rise in newtons per second for group. Trial A refers to warm-up interval; Trials B to E refer to first, second, third, and fourth exercise intervals; and Trial F refers to cooldown interval.

Trials	HR Mean Average		
	GAME^{Wheels} (SD)	No GAME^{Wheels} (SD)	*p* Value
A	101.6 (11.7)	103.5 (8.1)	0.520
B	119.0 (13.3)	116.7 (15.3)	0.690
C	127.0 (16.3)	116.5 (12.2)	0.024*
D	129.2 (19.5)	115.0 (12.3)	0.007*
E	130.4 (20.0)	115.5 (12.5)	0.005*
F	120.9 (18.2)	108.3 (10.3)	0.016*

*Significant differences.

the pushrim. The combination of a smaller impact spike and a longer time of hand contact with the pushrim may lead to a decreased possibility of secondary injuries. The number of propulsion strokes may be altered during this time, and stroke cadence has been shown to increase the possibility of a secondary injury [9]. The current study reported the males' hand-pushrim contact times during exercise were 0.57 s to 0.67 s, while the females were 0.58 s to 0.83 s. These times are longer than the hand-pushrim contact times of 0.40 s and 0.30 s reported by Boninger et al. during wheelchair propulsion at 1.3 m/s and 2.2 m/s, respectively [11].

These results support the concept that wheelchair users in the current study kept their hands on the pushrims longer to control the racecar. The video game played may determine how much force is applied to the pushrim and the duration of hand contact with the pushrim. These are factors that individuals using the GAME^{Wheels} will need to know so that they are aware that a video game may change their propulsion pattern in a fashion that may lead to a secondary injury.

The position of the car on the racetrack was not recorded during kinetic data collection. This could have influenced the kinetic data if the individual was propelling down the straight portion of the racetrack versus turning the racecar. The results of the overall resultant force data imply that no changes were found in the propulsion patterns when comparing exercise with and without the video game. Future studies should investigate kinetic data during the turning of the racecar versus straight driving. Another factor that may have influenced the propulsive forces recorded is the number of times the individuals crashed the racecar or were stuck against virtual walls. During downtime from crashes or being stuck against a wall, the individual would not be propelling in their usual manner. The individual would have had to maneuver the car off the wall or around the other cars, thereby altering the forces. For this study, the number of "crashes" was not recorded. Futures studies may also try to increase the length of time that data are collected.

The maximum resultant forces recorded during this study were 60 N to 62 N with and 57 N to 60 N without the video game. Boninger et al. reported similar values at 0.9 m/s of 67 N [11]. The rate of rise reported in the current study was 860 N/s to 1070 N/s with and 830 N/s to 1020 N/s without the video. The kinetic results from this study are similar to other research with individuals propelling their wheelchairs at everyday speeds. Our results provide data that demonstrate exercise with the GAME^{Wheels} system might not alter the propulsion pattern in a detrimental way and could be a good alternative exercise device for manual wheelchair users.

CONCLUSIONS

The results from the two studies investigating the GAME^{Wheels} system indicate that increased physiological responses may be achieved with game play. Future studies would have to be completed to ascertain whether the system would help individuals increase their cardiovascular fitness level with exercise while playing a video game. Also the subjects verbally reported that they enjoyed being able to play a video game while exercising and that this system would help them to exercise more often and for longer periods of time.

Subjects exercised at a higher physiological level when using the GAME^{Wheels} system. Both oxygen consumption and ventilation were higher with game play. The significantly higher physiological data suggest that the human metabolic work was increased while the propulsion forces were not significantly higher. This may imply that exercise with the video game play might motivate the individual or stimulate a cardiac exercise response. Earlier research reported that physiological variables were elevated while individuals played video games while seated [19–22]. Involving the individual in the video game stimulates or excites the person, which in turn elevates the physiological variables. The major difference with wheelchair users is that they are using their muscles to play or control the game leading to a cardiovascular response, which can help maintain or increase their cardiovascular fitness level.

Future studies should address the limitations of this study, which include small sample size, as well as inclusion of more women. GAME[Wheels] should also be examined to determine if the system aids individuals who use wheelchairs to exercise regularly, resulting in positive physiological changes. Additional research should examine the system as a possible training tool for education on efficient wheelchair propulsion technique.

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