Department of Veterans Affairs

JRRD Volume 41, Number 3B Pages 421–428
May/June 2004
Journal of Rehabilitation Research & Development

The effects of rear-wheel camber on the mechanical parameters produced during the wheelchair sprinting of handibasketball athletes

Arnaud Faupin, BS; Philippe Campillo, MS; Thierry Weissland, MS; Philippe Gorce, PhD; André Thevenon, PhD
Laboratoire d'Etudes de la Motricité Humaine, Université de Lille 2, Faculté des Sciences du Sport et de l'Education Physique, Lille, France; Centre de L'ESPOIR, Lille, France; Laboratoire Ergonomie du Sport et Performance, Université de Toulon-Var, La Garde Cedex, France; Centre Hospitalier Régional Universitaire de Lille, Service de Médecine Physique et de Réadaptation Fonctionnelle, Unité d'Analyse du Mouvement, Lille Cedex, France

Abstract—The wheel camber of a wheelchair is a significant parameter that must be taken into account in the search for optimal regulation of a wheelchair. This study examined the effects of different rear-wheel camber (9°, 12° and 15°)—today used mainly in the handibasket championship—on the various kinetic and kinematic parameters of the propulsion cycle. Eight males, all players in the French handibasket championship, were asked to participate in this study. They performed three 8 s maximal sprints as measured by a wheelchair ergometer, 9°, 12°, and 15° of rear-wheel camber. The results of our study show that residual torque increases in proportion to the increase in wheel camber. This could explain other study results, which show a decrease in mean velocity and an increase in both power output and time of the propelling phase, in relation to the wheel camber. These results should provide the information necessary for optimal wheelchair regulation.

Key words: basketball, biomechanics, camber, propulsion, wheelchair ergometer.

INTRODUCTION

The wheel camber of a wheelchair is a significant parameter that must be taken into account in the search for optimal regulation of a wheelchair. Camber is defined in several ways in the literature. According to Higgs, camber is "the angle of the main wheel to the vertical" [1], while Frank and Abel define it as a situation in which "the spacing between the top points of the wheels may be less than the spacing between the bottom points" [2].

Wheel camber has direct effects on several parameters. For instance, increasing camber slightly reduces the height of the seat, while it proportionally increases the wheelbase, which corresponds to the width of the wheelchair. In the same way, with negative camber, the center of gravity of the occupied wheelchair moves backward [3]. From a practical point of view, increased wheel camber improves hand protection as chairs pass through doors and, in terms of handibasket, it helps prevent contact between wheelchairs during a match [4]. Increased wheel camber also provides better lateral static stability for the wheelchair [5] and shortens the down turning moment [6]. Moreover, Faupin et al. have shown that increasing wheel camber improves basketball players' turn velocity [7].

Abbreviation: FHF = French Handisport Federation.

This material was based on work supported by Laboratoire d'Etudes de la Motricité Humaine, Université de Lille 2, Faculté des Sciences du Sport et de l'Education Physique, Lille, France.

Address all correspondence to Philippe Campillo, Laboratoire d'Etudes de la Motricité Humaine (EA 3608), Université de Lille 2, Faculté des Sciences du Sport Et de l'Education Physique (FSSEP), 9 rue de l'Université, 59790 Lille, France; +33-320-88-73-69; fax: +33-320-88-73-63; email: pcampillo@hp-sc.univ-lille2.fr.

Scientific data pertaining to the effects of camber on physiological responses are limited, and those that exist vary significantly depending on the authors and the test protocols used. For example, while Veeger et al. observed no significant effect on physiological responses in able-bodied subjects propelling a wheelchair whose wheel camber varied between 0°, 3°, 6° and 9° [4], Buckley and Bhambhani concluded that the energy cost of wheelchair propulsion increased with camber angle [8]. In addition, several authors have proposed that increasing rear-wheel camber would both make it easier to reach the hand rims, and facilitate arm movement during the propulsion cycle [4,9]. It has also been suggested that increased camber would provide a more effective application of force and lower energy losses [10].

The effect of wheel camber on overall rolling resistance is a controversial subject in the literature: the various published results are contradictory [11]. Veeger et al. found that rolling resistance decreases with increasing camber angle in a minor, but significant, difference [4]. Other researchers have concluded that rolling resistance is negligible [8,12]. Further, Weege theoretically supports the hypothesis according to which that rolling resistance would increase proportionally with increasing wheel camber [13]. Our 2002 study, which used a wheelchair ergometer, tends to confirm the findings of Weege rather than those of Veeger [14].

Within-cycle parameters have also been described frequently in the literature [4,11,15–21]. Among these studies, Vanlandewijck et al. was particularly interested in wheelchair basketball propulsion [15,17]. To our knowledge, among the many researchers publishing in this area, only Veeger et al. have studied the incidence of wheel camber on the different kinematic parameters [4]. The data obtained in their study indicate that a 0° to 9° wheel camber modifies push time and push angle significantly. However, because of minor changes in wheel alignment, the authors had to compensate for the differences of rolling resistance and, their test group included only able-bodied subjects.

The present study examined the effects of increased rear-wheel camber (9°, 12° and 15°) on the mechanical parameters of the propulsion cycle. A group of elite wheelchair basketball athletes was asked to participate. A wheelchair ergometer measured the parameters under examination: the resistance to advancement required for the user-to-chair interface, the force and the power output developed by the user, as well as the velocity and the time of the various propulsion cycles. Our results should provide the information necessary for optimal wheelchair regulation.

METHODS

Subjects

The sample group consisted of eight experienced male athletes, all players in the French handibasket championship. **Table 1** presents the averages and standard deviations of subject age, mass, and height, as well as the number of training hours/week. The French Handisport Federation (FHF) classifications, which correspond to individual disability levels, are also presented for each athlete. The FHF classifications varies from 1 to 5: the lower the classification, the heavier the athlete's disability and vice versa. Written informed consent was obtained from all subjects, in full knowledge of what the experiments entailed.

Table 1.
Mean and standard deviation of subject data.

Subject	Age (yr)	Mass (kg)	Height (cm)	Classification (1 to 5)	Sports Training (h/wk)
1	25.0	75.0	180.0	4.5	6.0
2	24.0	52.0	180.0	2.0	6.0
3	24.0	68.0	175.0	5.0	4.0
4	27.0	60.0	168.0	4.0	6.0
5	22.0	103.0	194.0	5.0	6.0
6	20.0	36.0	150.0	2.0	4.0
7	32.0	68.0	168.0	4.0	6.0
Mean	24.9	66.0	173.6	3.8	5.4
Standard Deviation	3.6	19.2	12.6	1.2	0.9

Instrumentation

A Top End X-Terminator-type basketball wheelchair, weighing 13 kg and measuring 80 cm long, was selected for use in this study. The angle formed by the back and the seat was 75°. The back, positioned vertically, was 28 cm high; its width and depth were, respectively, 42 cm and 39 cm. The diameter of the wheels was 64 cm, with tubeless tires inflated to 8 bars. Once all these parameters had been measured and controlled, they were not changed. Only wheel camber was varied (9°, 12°, 15°). These variations caused the respective modifications of the wheelbase (68 cm, 70 cm, and 72 cm) and the seat height (28 cm, 27.3 cm, and 26.5 cm). After each camber change, we paid special attention to the alignment of the rear wheels to avoid misalignment, also called "toe in" and "toe out" [22]. The top-to-top wheel distance remained constant for each camber [4].

The wheelchair was placed on a new model ergometer (VP100 HANDI, HANDISOFT, HEF Tecmachine, France) (**Figure 1**). This ergometer, built on the lines of the recently validated VP100 HTE ergometer, consists of a roller system driven by the wheels of the wheelchair [23]. Two electromagnetic brakes (Type ZS, Friedrichshafen, Germany), one on each side of the roller system, are mounted on a force sensor that can compel the wheelchair to brake, producing a braking torque from 0 Nm to 4 Nm. Two sensors of instantaneous velocity by incremental encoders (3,600 points per rotation) also complete the ergometer.

The velocity and force signals were sampled at 100 Hz and then transferred to a National Instruments 6024 E data acquisition card in a computer (Victor Technologies 386SX). These high frequencies allowed the analyses of the propulsion cycle. The roller system was calibrated, with the manufacturer's help, prior to the beginning of the study.

Data Analysis

In our study, data from all the trials were recorded, but we only took into account the last five cycles of the 8 s sprints, when the different variables to be calculated had stabilized and reached a plateau. All data were filtered by means of a low-pass filter at cut-off frequency of 10 Hz. **Figure 2** presents a graph of the velocity and power parameters during an 8 s sprint for one subject. For each sprint, we calculated the data corresponding to the mean velocity per arm cycle (V_m), the cycle time (C_t), the time of the propelling phase (P_t: pulling and pushing phases during which the user drives the wheels of his wheelchair), and the time of the nonpropelling phase (R_t: phase during which the user's hands are positioned to restart the push phase). The time parameters (C_t, P_t, R_t) were determined according to the acceleration and deceleration phases of the wheels as observed on the instantaneous speed curve.

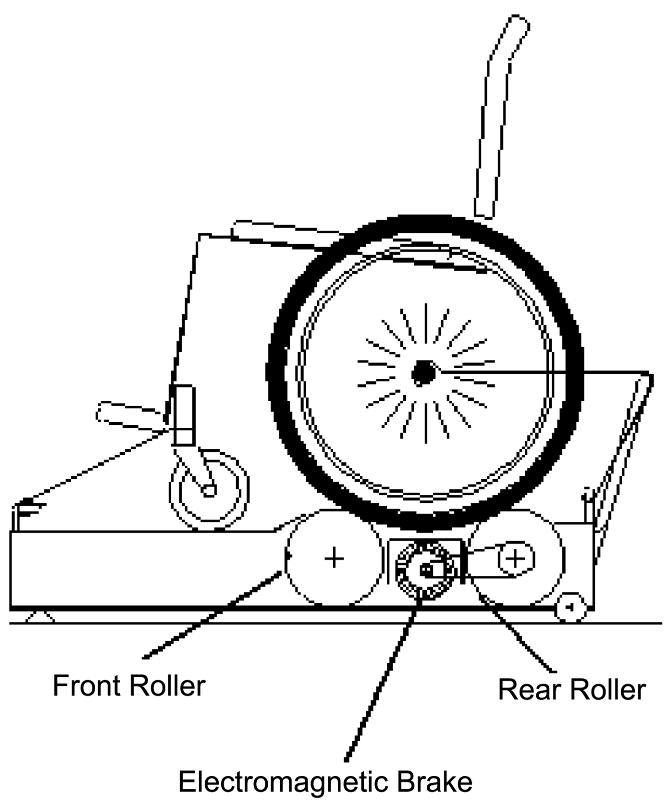

Figure 1.
Wheelchair on ergometer. Reprinted with permission of HEF Tecmachine, France.

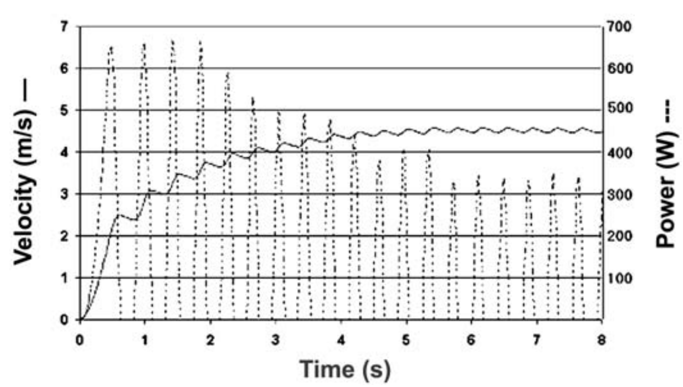

Figure 2.
Velocity and power output developed by one subject during 8 s sprint test.

The total power output developed during the push phase (P_{tot}, **Equation (1)**, below) corresponds to the sum of the power developed to overcome the total inertia of the rollers (P_i) and the total brake power (P_b) according to:

$$P_{tot} = P_i + P_b \ , \quad (1)$$

where P_i and P_b are, respectively,

$$P_i = (T_i) \quad (2)$$

$$P_b = (T_r), \quad (3)$$

and where T_i (Nm) is the torque needed to overcome inertia (m^2kg) calculated instantaneously from the two sensors of force mounted on each side of the roller system, and (rad·s^{-1}) is the angular velocity of the rollers (roller circumference: 502.65 mm) obtained by means of the two sensors of instantaneous velocity.

Residual torque (T_r) is due to the distortion of the tire on the rollers, and the rolling resistance of both the rollers and wheelchair ballbearings. The T_r value is the measurement of the deceleration time between initial velocity and final velocity [23,24].

Procedures

Once settled in the wheelchair fixed to the ergometer, the subject had 10 min to get used to the equipment before beginning the test. Prior to each sprint, residual torque was evaluated according to the Thiesen method [24]. After a familiarization period that also served as a warm-up, the subject completed two or three maximal pushes on the hand rim and then maintained the predetermined, "standard" position until the wheels came to a complete stop. The standard position—trunk slightly tilted forward, elbows on the knees, chin in the hands—was imposed on all subjects throughout the testing. T_r was directly measured by the ergometer during this deceleration phase.

All the subjects were asked to perform three 8 s maximal sprints in a random order, while positioned on a wheelchair ergometer. They completed the same test for the following three wheel cambers: 9°, 12°, and 15°. At a signal given by the experimenter, the subjects were encouraged to sprint as fast as possible for 8 s. A 5 min rest period was imposed before each new sprint, during which time the wheelchair and the roller ergometer were adjusted. No instruction was given to the subjects concerning either the position of their hands on the hand rim or their chosen propulsion technique.

Statistical Analysis

The averages and standard deviations of all parameters were calculated for each experimental situation. The use of a nonparametrical statistical test was necessary because the requirements for parametrical tests—namely, the normal distribution and the covariance homogeneity of the source population—were not satisfied. Given these constraints, the Friedman test appeared the most suitable. The Spearman method was used for correlation testing. The level of significance was set at $p < 0.05$. All statistical analyses were performed with SPSS (Service Provisioning System Software).

RESULTS

The means and standard deviations of the temporal, kinetic, and kinematic variables are presented in **Table 2**. The increase in wheelchair camber was associated with significant increases in T_r and P_{tot}, and a significant decrease in V_m. As for the temporal variables, no significant difference was found for C_t and R_t. However, significant differences were observed for P_t.

For each subject, two linear relations were verified: one between V_m and wheel camber (9° to 15°) with a determination coefficient between $0.95 < R^2 < 1$, and another between T_r and wheel camber with a determination coefficient between $0.96 < R^2 < 1$ (**Figure 3**). When T_r increases with wheel camber, V_m decreases.

Finally, to determine whether a relation exists between T_r and V_m, we performed the Spearman correlation test. This test revealed that these two variables were linked ($p = 0.027$ with a negative correlation coefficient = –0.485).

DISCUSSION

This study, much like the study we completed in 2002 [14], indicates that residual torque T_r (0.64 ± 0.12, 0.97 ± 0.16, and 1.35 ± 0.22 Nm) increases in proportion to the increase in rear-wheel camber, from 9° to 12° to 15°. When changing camber, we paid particular attention to the parallelism of the rear wheels to avoid "toe in" or

Table 2.
Values (mean ± standard deviation) of residual torque (T_r), mean velocity (V_m), inertia power (P_i), brake power (P_b), total power (P_{tot}), cycle time (C_t), propelling time (P_t), recovery time (R_t) measured on each wheel camber condition.

Camber	9°	12°	15°	*p*-value
T_r (Nm)	0.64 ± 0.12	0.97 ± 0.16	1.35 ± 0.22	0.001*
V_m (km/h)	14.46 ± 1.16	13.40 ± 1.21	12.56 ± 1.39	0.001*
P_i (W)	112.90 ± 26.70	141.54 ± 26.05	167.06 ± 30.86	0.002*
P_b (W)	60.14 ± 10.29	87.12 ± 13.81	109.69 ± 13.16	0.001*
P_{tot} (W)	173.03 ± 35.68	228.65 ± 36.19	276.75 ± 37.26	0.002*
C_t (ms)	414.29 ± 28.35	412.86 ± 38.05	424.43 ± 27.15	0.664
P_t (ms)	145.71 ± 25.50	150.00 ± 15.52	157.14 ± 10.24	0.008*
R_t (ms)	268.57 ± 32.45	262.86 ± 26.06	267.14 ± 25.36	0.692

*Significant difference ($p < 0.01$).

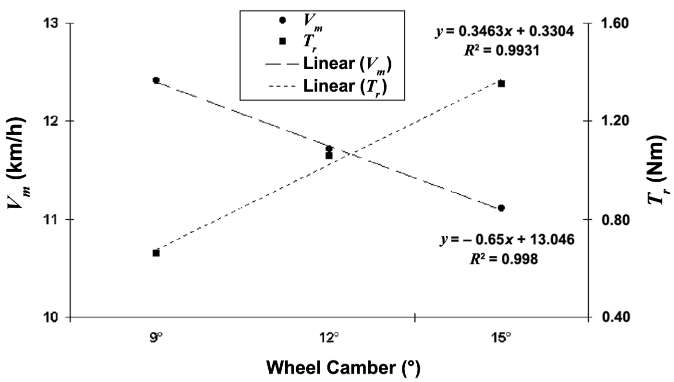

Figure 3.
Linear regressions between V_m and wheel camber, and T_r and wheel camber, for one subject.

"toe out," a misalignment of the wheels that would have increased rolling resistance [2,12,22,25]. Despite these precautions, our results tend to confirm Weege's hypothesis that rolling resistance would increase proportionally with the increase in wheel camber [13], rather than the results of Veeger et al, who maintained that rolling resistance decreased with increasing camber angle in a minor effect [4]. There are several possible reasons for the differences between our results and those of Veeger et al. [4]. In the Veeger study, a treadmill was used to take the rolling resistance of the wheelchair casters into account, which is impossible when it is used an ergometer [26]. In addition, the Veeger study, done in 1989, examined wheel cambers between 0° and 9°, while in our study camber varied from 9° to 15°; these values were chosen because these are the wheel cambers most often used in the present-day French handibasket championship. Finally, Veeger et al. tended to ascribe their results to a minor change in wheel alignment for which they could not compensate. However, in our study, the alignment of the wheels was controlled. Therefore, the difference in rolling resistance is not due to a misalignment of the wheels. One of the most suitable hypothesis is that when increasing wheel camber, the contact between the tires and the court surface increases proportionally, causing an increase of rolling resistance. A limitation of our study is that, on an ergometer, this phenomenon tends probably to be amplified for two reasons. First, the contact between the tires and the rollers is more important on an ergometer [26]. Second, on a two-roller system, wheel camber is likely to lead to misalignment to one of the rollers and therefore to an increase in rolling resistance. Thus, the end of this discussion is only valid in tests in the laboratory on roller ergometers and cannot be generalized to field tests. It would be interesting, in a future study, for investigators to conduct a field test to assess rolling resistance [27] in order to compare the results with those obtained in our study.

In our study of wheel camber varying from 9° to 15°, the mean velocities per arm cycle V_m were 14.46 ± 1.16, 13.40 ± 1.21, and 12.56 ± 1.39 km/h, respectively. These velocity values are comparable to those found by Veeger et al., during 20 s sprints (15.19 ± 1.22 km/h), where no braking was imposed by the ergometer [28]. According to Sanderson and Sommer, at such a velocity, the hand of the athlete moves more slowly than the wheel, which causes a braking force at the moment of initial hand-to-wheel contact [29]. Had we chosen to use video analysis techniques in our study, this hypothesis could have been verified.

The statistical data obtained in this study have shown significant differences between the V_m and T_r parameters, for the different wheel cambers (**Table 2**). In fact, there are significant linear relations between these two parameters and wheel camber for all the subjects (**Figure 3**). A significant relationship has also been established between V_m and T_r (p = 0.027, with a negative correlation coefficient = –0.485). Our results are closely akin to those of others authors, who have noted that increasing rolling resistance brought about a proportional decrease of the angular velocity of the wheels [28,30]. However, these authors deliberately increased rolling resistance by successively increasing the load, whereas in our study, the increase in rolling resistance was both involuntary and much less important than that of the other studies.

From the statistical analysis of the results, we have observed significant differences in the power output parameters (**Table 2**). The results demonstrate that P_i, P_b, and P_{tot} increase in proportion to the three different degrees of wheel camber (9°, 12°, 15°). To our knowledge, no other study has examined these parameters in terms of wheel camber. For this reason, it is difficult to compare our results with those in the literature because the values obtained may be very different from one study to another. In fact, Veeger et al. have shown an important variability in the power developed by the subject during the push phase, when the rolling resistance imposed by the ergometer is modified [28]. Their values, obtained from the left arm only, were between 93.3 ± 23.4 and 186.0 ± 41.7 W. In addition, the power values shown in the literature often correspond to the power levels calculated over the total time of the cycle.

The temporal parameters, C_t and R_t, do not seem to vary with wheelchair wheel camber; at least, no significant difference was observed (**Table 2**). However, there was an increase in P_t proportional to the wheel camber (respectively, 145.71 ± 25.50 ms, 150.00 ± 15.52 ms, and 157.14 ± 10.24 ms for 9°, 12°, and 15°). This increase can be explained in two ways. Either an increase of R_t, due to the increase of wheel camber, modifies the push time, or the increase in wheel camber has a direct effect on P_t. In defense of the first explanation are the observations of Veeger et al., who maintain that stronger rolling resistance leads to prolonged hand-wheel contact, which makes the push time longer [28]. However, the second explanation tends to support another Veeger et al. study, in which it was demonstrated that wheel camber has significant effects on push time, because increasing wheel camber causes changes in the athlete's grip on the hand rim [4].

CONCLUSION AND PERSPECTIVES

We have used an ergometer to estimate the influence of wheelchair wheel camber on several of the kinetic and kinematic parameters of wheelchair propulsion cycles. Our results have demonstrated an increase in residual torque (T_r) proportional to the increase in wheel camber (from 9° to 12° to 15°). This increased rolling resistance could explain the other results produced in this study, which showed a decrease of mean velocity (V_m) and an increase of power output in relation to the wheel camber. As far as temporal parameters are concerned, the time of the propelling phase (P_t) is the only parameter that tends to increase in proportional to the increase in wheel camber.

These results would appear to prove that, at least in laboratory tests using roller systems, a wheelchair's wheel camber influences the various parameters just mentioned. Even though an increase in wheel camber has numerous advantages (for example, better stability, and an improvement of a basketball player's turning speed), the seemingly negative effect of camber angle on propulsive action must also be taken into account to obtain the optimal regulation of the wheelchair.

Careful consideration of the camber angle becomes even more important when one realizes that 64 percent of wheelchair basketball gametime is spent in propulsive actions [31]. Players have to find the best compromise, in terms of their handicap, their position on the court, and their playing level. In addition, it is important to remember that while camber angles differ, the basketball wheelchair wheels are all the same. The contact between the tires and the court surface is modified by the wheel camber, which may explain why rolling resistance also increases. Wheelchair builders could take this into account and propose wheels and tires appropriate to each camber angle.

Several directions for future research are possible. For example, the use of a three-dimensional analysis system, interfaced with a wheelchair ergometer, would allow a more precise analysis of the propulsion cycles. Thus, it would be possible to verify the hypothesis that increased wheel camber is likely to improve the application of hand rim force during the push phase. But before, it would be interesting for the rolling resistance on court to be measured [27] so the results could be compared with those obtained in our study.

ACKNOWLEDGMENT

We thank HEF Tecmachine (rue Benoit Fourneyron-ZI sud, 42166 andrezieux-Boutheon, France) for having put their new ergometer (VP 100 HANDI) at our disposal.

REFERENCES

1. Higgs C. An analysis of racing wheelchairs used at the 1980 Olympic Games for the Disabled. Res Quart Exerc Sport. 1983;54(3):229–33.
2. Frank TG, Abel EW. Drag forces in wheelchairs. In: van der Woude LHV, Meijs PJM, van der Grinten BA, editors. Ergonomics of manual wheelchair propulsion: state of the art. Amsterdam: IOS Press; 1993. p. 255–67.
3. Trudel G, Kirby RL, Bell AC. Mechanical effects of rear-wheel camber on wheelchairs. Assist Technol. 1995;7(2): 79–86.
4. Veeger D, van der Woude LH, Rozendal RH. The effect of rear-wheel camber in manual wheelchair propulsion. J Rehabil Res Dev. 1989;26(2):37–46.
5. Trudel G, Kirby RL, Ackroyd-Stolarz SA, Kirkland S. Effects of rear-wheel camber on wheelchair stability. Arch Phys Med Rehabil. 1997;78(1):78–81.
6. Tomlinson JD. Managing maneuverability and rear stability of adjustable manual wheelchairs: an update. Phys Ther. 2000;80:904–11.
7. Faupin A, Campillo P, Weissland T, Micallef JP. Effect of the wheel camber of a wheelchair on the linear speed and on the speed of turning of the basketball player. Cinésiologie. 2002;201:4–6.
8. Buckley SM, Bhambhani YN. The effects of wheelchair camber on physiological and perceptual responses in younger and older men. Adapt Phys Act Quart. 1998;15:15–24.
9. van der Woude LHV. The wheelchair-user interface: the core of ergonomics. In: van der Woude LHV, Meijs PJM, van der Grinten BA, editors. Ergonomics of manual wheelchair propulsion: state of the art. Amsterdam: IOS Press; 1993. p. 271–92.
10. Vanlandewijck Y, Theisen D, Speapen A. Le cycle de propulsion: biomécanique, cinétique et cinématique. In: Simon L, Pélisser J, Hérisson C, editors. Le fauteuil roulant. Paris: Masson Press; 1997. p. 69–83.
11. van der Woude LH, Veeger HE, Dallmeijer AJ, Janssen TW, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys. 2001;23(10):713–33.
12. O'Reagan J, Thacker J, Kauzlarich J, Mochel E, Carmine D, Bryant M. Wheelchair dynamics. In: Wheelchair mobility, 1976–1981. Rehabilitation Engineering Center, University of Virginia; 1981. p. 33–41.
13. Weege RD. Technische Voraussetzungen fur den Aktivsport im Rollstuhl. Orthopaedie Technik. 1985;36(6):395–402.
14. Faupin A, Campillo P, Weissland T, Micallef JP. Effect of wheel camber and various positions of the subject on the total wheelchair resistance, using an ergometer. Proceedings of the XXVIIième Congrès de la société de Biomécanique, 2002 Sept 12–13, Valenciennes, France. Arch Int Physiology Bioch. 2002;110 Suppl(Sept):48.
15. Vanlandewijck Y, Theisen D, Daly D. Wheelchair propulsion biomechanics: implications for wheelchair sports. Sports Med. 2001;31(5):339–67.
16. Vanlandewijck YC, Spaepen AJ, Lysens RJ. Wheelchair propulsion efficiency: movement pattern adaptations to speed changes. Med Sci Sports Exerc. 1994;26:1373–81.
17. Vanlandewijck YC, Spaepen AJ, Lysens RJ. Wheelchair propulsion: functional ability dependent factors in wheelchair basketball players. Scand J Rehab Med. 1994;26:37–42.
18. van der Woude LH, Hendrich KM, Veeger HE, van Ingen Schenau GJ, Rozendal RH, de Groot G, Hollander AP. Manual wheelchair propulsion: effects of power output on physiology and technique. Med Sci Sports Exerc. 1988; 20(1):70–78.
19. van der Woude LHV, Veeger HEJ, Rozendal RH, van Ingen Schenau GJ, Rooth F, van Nierop P. Wheelchair racing: effects of rim diameter and speed on physiology and technique. Med Sci Sports Exerc. 1988;20(5):492–500.
20. van der Woude LHV, Veeger HEJ, Rozendaal RH. Ergonomics of manual wheelchair propulsion: a prerequisite for optimum wheeling conditions. Adapt Phys Act Quart. 1989;6:109–32.
21. Veeger HE, van der Woude LH, Rozendal RH. Wheelchair propulsion technique at different speeds. Scand J Rehabil Med. 1989;21(4):197–203.
22. Kauzlarich JJ. Wheelchair rolling resistance and tyre design. In: van der Woude LHV, Hopman MTE, van Kemenade C, editors. Biomedical aspects of manual wheelchair propulsion: state of the art II. Amsterdam: IOS Press; 1999. p. 158–72.
23. Devillard X, Calmels P, Sauvignet B, Belli A, Denis C, Simard C, Gautheron V. Validation of a new ergometer adapted to all types of manual wheelchair. Eur J Appl Physiol. 2001;85(5):479–85.
24. Theisen D, Francaux M, Fayt A, Sturbois X. A new procedure to determine external power output during hand rim wheelchair propulsion on a roller ergometer: a reliability study. Int J Sports Med. 1996;17(8):564–71.

25. Barbosa Rodrigues P, Arlindo F, Silva Carrilho A, Antunes P. The relationship between the angle of camber and the tracking misalignment of manual wheelchairs. Proceedings of the RESNA ’96 Annual Conference. June 7–12 1996; Salt Lake City, Utah.
26. Martin X, Tordi N, Bougenot MP, Rouillon JD. Critical analysis of apparatus and evaluation methods for determination of physical capacity of spinal cord injured people using wheelchair. Sci Sports. 2002;17(5):209–19.
27. Vinet A, Bernard PL, Ducomps C, Selchow O, Le Gallais D, Micallef JP. A field deceleration test to assess total wheelchair resistance. Int J Rehabil Res. 1998;21(4):397–401.
28. Veeger HE, van der Woude LH, Rozendal RH. Within-cycle characteristics of the wheelchair push in sprinting on a wheelchair ergometer. Med Sci Sports Exerc. 1991;23(2): 264–71.
29. Sanderson DJ, Sommer HJ 3rd. Kinematic features of wheelchair propulsion. J Biomech. 1985;18(6):423–29.
30. Hintzy-Cloutier F, Tordi N, Rouillon J-D, Belli A. The influence of within-cycle pattern characteristics on mechanical parameters developed during wheelchair sprinting? Sci Sports. 2002;17(5):128–31.
31. Coutts KD. Dynamics of wheelchair basketball. Med Sci Sports Exerc. 2001;24(2):231–34.

Submitted for publication April 10, 2003. Accepted in revised form November 18, 2003.