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The effect of a novel square-profile hand rim on propulsion technique of wheelchair tennis players

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ABSTRACT

The purpose of this study was to investigate the effect of a square-profile hand rim (SPR) on propulsion technique of wheelchair tennis players. Eight experienced wheelchair tennis players performed two sets of three submaximal exercise tests and six sprint tests on a wheelchair ergometer, once with a regular rim (RR) and once with a SPR. Torque and velocity were measured continuously and power output and timing variables were calculated. No significant differences were found in propulsion technique between the RR and SPR during the submaximal tests. When sprinting with the racket, the SPR showed a significantly lower overall speed (9.1 vs. $9.8\ \mathrm{m\,s^{-1}}$), maximal speed (10.5 vs. $11.4\ \mathrm{m\,s^{-1}}$), and maximal acceleration (18.6 vs. $10.9\ \mathrm{m\,s^{-2}}$). The SPR does not seem to improve the propulsion technique when propelling a wheelchair with a tennis racket in the hand. However, the results gave input for new hand rim designs for wheelchair tennis.

1. Introduction

Sports for people with a disability started after World War II when Sir Ludwig Guttmann started to introduce competitive sports as integral part of spinal cord injury rehabilitation. In 1960, the first Paralympic games were held in Rome (Gold and Gold, 2007). Wheelchair tennis was at the Paralympic games for the first time in Barcelona in 1992 (International Tennis Federation, 2017). Since then wheelchair tennis has grown and became more popular and professional.

For professional wheelchair tennis players, it is important to optimize the performance while reducing the risk of injuries (Churton and Keogh, 2013). That can be done by optimizing the athlete himself (e.g. tennis skills, fitness) but also by improving the wheelchair or the wheelchair-user interface (Bascou et al., 2012; Mason, 2011). Wheelchair ergonomics have been studied previously (Van der Woude et al., 1986; Van der Woude et al., 2001) but mainly in daily wheelchair propulsion. Previous wheelchair tennis studies showed that the interface between the player and wheelchair is not optimal when propelling the wheelchair with a racket in the hand (de Groot et al., 2017; Goosey-Tolfrey and Moss, 2005). The speed is lower when propelling with a racket in the hand (Goosey-Tolfrey and Moss, 2005) and this can be explained by the higher power loss that is visible when the racket hand has to (de-)couple to the hand rim compared to propulsion without a racket (de Groot et al., 2017). Subsequently, a higher mean and peak power output is generated during the push phase to overcome these power losses before and after the push phase (de Groot et al., 2017). On the long term, this higher power generation on the racket hand might lead to overuse injuries of the upper extremity. To optimize performance and to prevent overuse injuries, it might be an option to change the ergonomic design of the hand rim to improve the (de-)coupling of the racket hand to the rim.

A previous study with able-bodied participants found no effects of different hand rim designs, i.e., shapes and coating, on propulsion technique and physiological measures under submaximal conditions in a wheelchair ergometer (Van der Woude et al., 2003). In contrast, another hand rim study showed that a larger rim tube diameter yielded slightly but significantly better values for physiological parameters, possibly due to a better grip and therefore less stabilization by the larger muscle groups, while no differences were seen in propulsion technique parameters (Van der Linden et al., 1996). Two studies investigated commercially available hand rims, the NaturalFit (Koontz et al., 2006) and the FlexRim (Richter et al., 2009). The NaturalFit consists of a smooth oval surface for the palm of the hand and a higher-friction contoured slot for the thumb. The FlexRim has a regular rim but consists of a high friction elastic membrane that spans between the hand rim and wheel rim. Biomechanical differences were found when

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Fig. 1. The square-profile rim.

these new rims were compared to a regular rim. The NaturalFit showed reduced grip moments during a slow speed test while the peak resultant forces were higher during a fast speed test (Koontz et al., 2006). The FlexRim showed reductions in both peak and total forearm muscle activation (Richter et al., 2006) and oxygen cost (Richter et al., 2009). However, all these studies did not involve holding a tennis racket during propulsion.

One of the French wheelchair tennis players, i.e., Stéphane Houdet – former number 1 of the world, won several Grand Slam tournaments and medals in the Paralympics -, started to play with a hand rim with a square profile. The assumption is that this profile might make it easier to hold the racket against the rim due to the flat and larger surface of the rim (Fig. 1). Due to the possibly easier coupling of the hand with the racket to this square-profile rim, the power loss during coupling seen with the regular rim might decrease and subsequently the peak power output exerted during the push phase might decrease. In the end, this might lead to higher speeds but also to less overuse injuries of the upper extremity. No studies have yet addressed whether this square-profile hand rim is indeed advantageous regarding propulsion technique. Therefore, the objective of our study was to investigate the effect of this square-profile rim on the propulsion technique compared to a regular rim. The hypothesis is that propulsion technique - more specifically the power loss during (de-)coupling of the racket hand to the rim and subsequently the peak power output during the push phase - improves when using such a square-profile rim. To that end, a square-profile rim was developed (Fig. 1) to be able to test this assumption in a group of elite wheelchair tennis players, both during steady-state (constant velocity) and sprint conditions.

2. Methods

2.1. Participants

Eight experienced wheelchair tennis players participated in this study. Participant characteristics are summarized in Table 1. Participant's height and body mass were measured before the exercise tests. All participants were right handed. Test protocols were approved by the ethical committee of the Faculty of Human Movement Sciences, VU University, Amsterdam, the Netherlands. All participants gave informed consent prior to participation.

2.2. Design

In this cross-sectional study, participants performed two sets of three submaximal exercise tests and six sprint tests on a wheelchair ergometer (specifications of this non-commercially available stationary, computer-controlled wheelchair ergometer can be found in Niesing et al. (1990)) with and without holding their own racket twice. One set was performed with the regular rim and the other set was performed with a square-profile rim. Fig. 2 shows the characteristics of the rims. The square-profile rim was made of carbon fiber. The top side of the rim, i.e., where the thumb is located in Fig. 1, has a tennis racket grip texture (Babolat Comfort Pro Team, Lyon, France). The other three sides of the rim were smooth. Order of the sets was randomized among the participants to avoid a possible learning effect. Participants had at least 10 min rest between the sets. Video recordings (Panasonic HC-V770, Osaka, Japan), were made during all tests to be able to observe how athletes coupled their hand and racket to the rims.

Table 1
Participant characteristics.

Personal characteristics	N or mean (SD)
Men/Women (N)	4/4
Age (years)	23.0 (6.4)
Body mass (kg)	63.4 (15.2)
Height (m)	1.72 (0.09)
Body mass index (kg/m^2)	21.3 (4.9)
Wheelchair tennis experience (years)	9.3 (5.1)
Disability	*N*
Paraplegia, incomplete	2
Paraplegia, complete	1
Spina bifida	2
Short femur, hip deviation	1
Hip dysplasia	1
Spastic legs	1
Wheelchair tennis level	*N*
International youth (N)	5
International adults (N)	3

2.3. Wheelchair ergometer

The wheelchair ergometer was fitted on both sides with either a regular hand rim or the newly developed square ones. The wheelchair ergometer measures the torque around the wheel axles and the velocity at each wheel (Niesing et al., 1990). The sample frequency for data collection was set at 100 Hz. Ergometer settings were individually adjusted whereby the adjustments were based as good as possible on the athlete's sitting position in the personal tennis wheelchair. The guidelines for the ergometer settings were: 1) the projection of the center of gravity of the body just lied behind the wheel axle when sitting upright; 2) When the arms were hanging down, the palm of the hand lied on the wheel axle; 3) The position of the seat is horizontal with the back seat in a 90° position with respect to the seat; 4) The height and tilt of the foot support was set like the participant preferred; 5) To keep the body in position, straps on the hips, legs and feet were used. The maximal camber position of the ergometer was used (12°).

2.4. Submaximal exercise test

After a warm-up/familiarization session of 1 min at a velocity of 1.0 m/s and a resistance of 0.15 W/kg (using the mass of the participant and the mass of an average tennis wheelchair (8 kg)) and a rest period of 30s, the submaximal exercise blocks started.

The first 3 min submaximal exercise block was performed without the racket, a speed of 1.5 m/s and a resistance of 0.15 W/kg. The second exercise block was performed with the racket at the same resistance and velocity. The last exercise block was also performed with the racket but now the resistance was set at 0.25 W/kg at a velocity of 1.5 m/s. The participants had 2 min of rest between the submaximal exercise blocks. These blocks were performed with the regular and square-profile hand rims in a counter-balanced order. The square-profile hand rim was placed on both sides to be able to investigate the effect of this rim on propulsion technique in the non-racket hand as well in a future study.

After each set of submaximal exercise tests, i.e., after each rim condition, participants answered two questions, one on their rating perceived exertion (RPE, score 0–10) and one to give an indication about how they experienced the grip (score: 1 (very bad) to 5 (very good)).

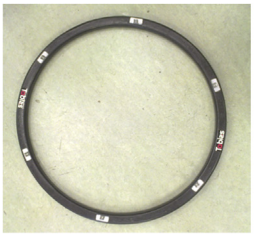
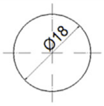
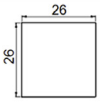
	Regular rim	**Square-profile rim**
Picture		
Size	26 & 27 inch	26 & 27 inch
Diameter rim	26 inch: 0.585 m 27 inch: 0.61 m	26 inch: 0.595 m 27 inch: 0.63 m
Rim profile (mm)		
Material	Aluminium	Carbon

Fig. 2. Characteristics of the regular rim and the square-profile rim.

2.5. Sprint test

During wheelchair tennis the player is almost always in motion. Therefore, the sprint test started immediately after a 30s warm-up at 0.25 W/kg. At the end of this warm-up period, the tester counted down and the sprint test started. The athlete was asked to propel the wheelchair as fast as possible for 5s. This protocol, which is partly based on Diaper and Goosey-Tolfrey (Diaper and Goosey-Tolfrey, 2009), was performed 6 times per hand rim: 3 times without the racket and 3 times with the racket. The three trials were averaged for a more reliable result (De Vet et al., 2011).

After the sprint tests, participants had to fill out the same questions as asked after the submaximal exercise tests, i.e. about their RPE and grip.

2.6. Data analysis

All ergometer data were analyzed using custom-written Matlab routines (Mathwork, Cambridge, MA, USA).

2.6.1. Submaximal exercise tests

Torque and velocity data were low-pass filtered with a recursive second-order Butterworth filter (cut-off frequency 10 Hz). The last minute of the exercise block was analyzed.

From the measured torque (M), wheel velocity (v_w) and wheel radius (r_w, 0.31 m) the power output was calculated:

$$\text{Power output} = M \cdot v_w \cdot {r_w}^{-1}$$

Peak and mean power output and velocity per push were calculated as the average of the mean and peak values over all completed pushes of each 60s period. Fig. 3 gives an example of what the power output signal looks like when pushing the hand rim twice.

The negative deflections or ‘dips’ at the start and end of the push phase were determined from the power output curve. The negative dips at the start of the push phase and at the end of the push phase were the most negative power output values at the start and the end of the push (Fig. 3).

Timing parameters were determined from the torque signal. Push time was defined as the time that the hand exerted a positive torque on the hand rim. Push time and recovery time together represent the cycle time. The push time was also expressed as a percentage of the cycle time. Frequency was defined as the number of complete pushes per minute. The work per push cycle was calculated as the power integrated over the wheel rotation angle.

The contact angle was calculated from the angular velocity and defined as the angle at the end of a push minus the angle at the start.

Lastly, the average speed and power output were calculated from start of the first push until start of the last push in the 60s period.

2.6.2. Sprint test

Torque and velocity data of the sprint tests were low-pass filtered with a recursive second-order Butterworth filter and cut-off frequency of 5 Hz. The same propulsion technique variables as described above for the submaximal test were calculated with the sprint test data. Furthermore, peak values of speed (km/h), acceleration (m/s^2) and power output (W) were calculated as well as the travelled distance (m) in 5 s. The acceleration was calculated by taking the derivative of speed, while for calculating the distance the speed signal was integrated.

2.7. Statistics

Descriptives of all outcome measures were calculated per exercise block for the racket hand and regular and square-profile rim separately.

A paired sample *t*-test was performed to study the differences in propulsion technique between the regular and square-profile rim when not holding a racket (block 1).

Repeated measures ANOVA (2 within factors: regular vs. square-profile rim; exercise block 2 (0.15 W/kg) and 3 (0.25 W/kg)) was used to check whether there are differences in propulsion technique of the racket hand between the regular and square-profile rim during the submaximal exercise blocks with racket.

The propulsion technique, averaged over the three sprints, of the racket hand was compared between the sprints with the regular and square-profile rim in the conditions with and without holding a racket, with a paired sample *t*-test.

Cohen's *d* or partial eta-squared (n_p^2) was calculated to determine the effect size. Statistical significance was set at $p < 0.05$. IBM SPSS statistics 20 (IBM Corporation, New York, USA) was used for all analyses.

3. Results

3.1. Submaximal exercise tests

No significant differences were found in propulsion technique between the hand rims when propelling the wheelchair without a racket in the hand, small to medium effect sizes were found (Table 2, block 1). When propelling the wheelchair with a racket in the hand, the square-

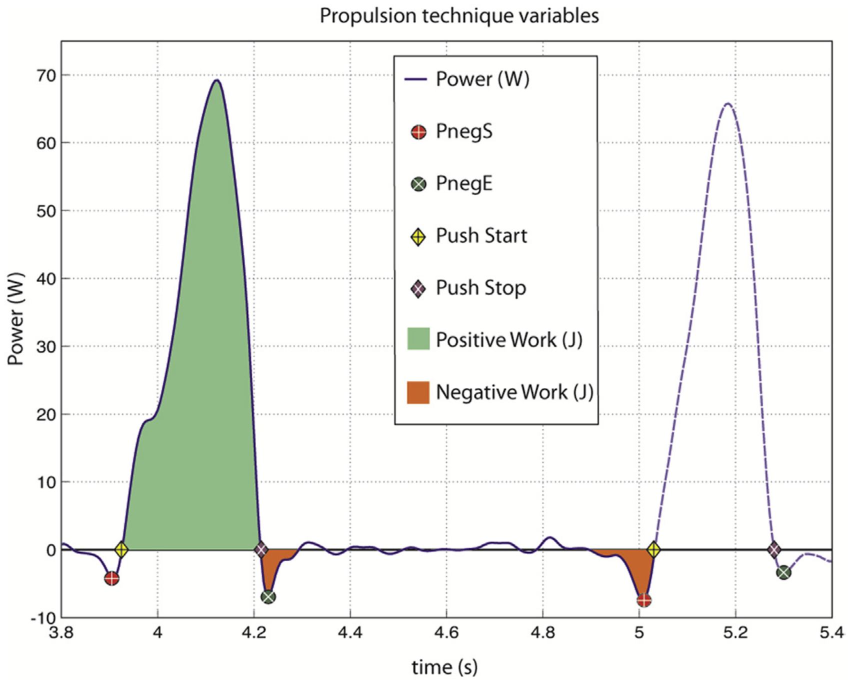


Fig. 3. Illustration of the definition of push time (from push start to push end), cycle time (from push start to push start), and power loss before (PnegS) and after (PnegE) the push time (Vegter et al., 2014).

Table 2
Mean (standard deviation) of the propulsion technique variables for the different conditions (with and without racket, regular and square profile) on the right side of eight experienced wheelchair tennis players.

Propulsion technique	Block 1 (0.15 W/kg)		p-value		Block 2 (0.15 W/kg)		Block 3 (0.25 W/kg)		p-value	
	Regular, without racket	Square, without racket	T-Test [a]	Effect size d	Regular, with racket	Square, with racket	Regular, with racket	Square, with racket	Rep Meas ANOVA[b]	Effect Size [c] n_p^2
Frequency (pushes/min)	54 (7)	52 (7)	0.372	0.34	54 (7)	56 (7)	58 (8)	57 (9)	0.435	0.089
Push time (s)	0.36 (0.05)	0.34 (0.05)	0.156	0.56	0.26 (0.03)	0.26 (0.01)	0.29 (0.02)	0.29 (0.02)	0.406	0.100
Cycle time (s)	1.15 (0.11)	1.17 (0.15)	0.519	−0.24	1.13 (0.15)	1.10 (0.15)	1.06 (0.15)	1.08 (0.16)	0.726	0.019
%Push time (%)	31.6 (5.6)	30.1 (6.1)	0.214	0.48	23.7 (3.4)	23.7 (2.5)	27.9 (2.7)	27.3 (2.9)	0.715	0.020
Contact angle (°)	109 (11)	106 (10)	0.338	0.36	83 (9)	79 (6)	90 (10)	87 (9)	0.196	0.225
POmean/push (W)	57.5 (14.1)	58.4 (13.3)	0.684	−0.15	79.5 (13.2)	78.5 (12.9)	112.8 (18.7)	110.1 (17.7)	0.608	0.039
POpeak/push (W)	113.2 (28.6)	113.5 (28.7)	0.956	−0.02	152.2 (26.0)	151.0 (22.5)	217.6 (33.4)	213.6 (29.7)	0.694	0.023
Work/push (J)	20.7 (3.5)	20.4 (3.9)	0.787	0.10	21.8 (3.7)	21.0 (3.6)	34.1 (7.1)	32.9 (5.7)	0.136	0.288
Negative PO start push (W)	−5.6 (1.4)	−5.2 (1.9)	0.568	−0.21	−17.2 (11.1)	−16.0 (5.2)	−15.0 (7.1)	−14.4 (4.9)	0.787	0.011
Negative PO end push (W)	−6.5 (2.3)	−6.4 (2.4)	0.846	−0.07	−8.9 (1.7)	−9.6 (3.9)	−10.9 (1.9)	−11.8 (3.8)	0.562	0.050
Mean overall speed (km/h)	5.3 (0.4)	5.2 (0.4)	0.979	0.01	5.3 (0.4)	5.2 (0.4)	5.2 (0.3)	5.1 (0.4)	0.406	0.100
Mean overall PO (W)	16.4 (3.5)	16.2 (4.4)	0.725	0.13	16.7 (3.8)	16.6 (3.0)	29.7 (6.6)	28.2 (5.3)	0.101	0.337

[a] T-test: right hand block 1 (without racket) vs. block 2 (with racket).
[b] Repeated measures: effect of racket for block 2 and 3.
[c] n_p^2partial eta-squared.

profile hand rim showed a similar propulsion technique compared to the regular hand rim, also shown by the small effect sizes (Table 2, block 2 and 3). Fig. 4 shows the individual results of the negative power output at the start of the push and POpeak during the push phase during exercise block 3 (0.25 W/kg with racket) performed with the regular rim vs. the square-profile rim.

No significant differences in RPE (regular: 3.4 ± 0.5, range: 3–4; square: 3.5 ± 0.8, range: 3–5; $p = 0.60$) and grip (regular: 3.6 ± 0.5, range: 3–4; square: 3.4 ± 1.1, range: 2–5; $p = 0.56$) were found between the rim conditions. Fig. 5 shows the distribution of answers to the scores for how the participant experienced the grip after the different rim and exercise conditions.

3.2. Sprint test

The results of the sprint tests are shown in Table 3. No differences were found in propulsion technique between the regular and square-profile hand rim when riding without a racket in the hand, except for the maximal acceleration. The maximal acceleration was significantly lower when propelling the wheelchair with the square-profile hand rim without holding a racket.

When sprinting with racket in the hand, several propulsion technique variables were significantly different or showed a trend ($p = 0.053$–0.076) when the regular hand rim was compared with the square-profile hand rim. The square-profile hand rim showed a significantly lower overall sprint speed, maximal speed, and maximal acceleration. Furthermore, the square-profile hand rim showed a trend ($0.05 < p < 0.08$) for a lower push frequency, higher cycle time,

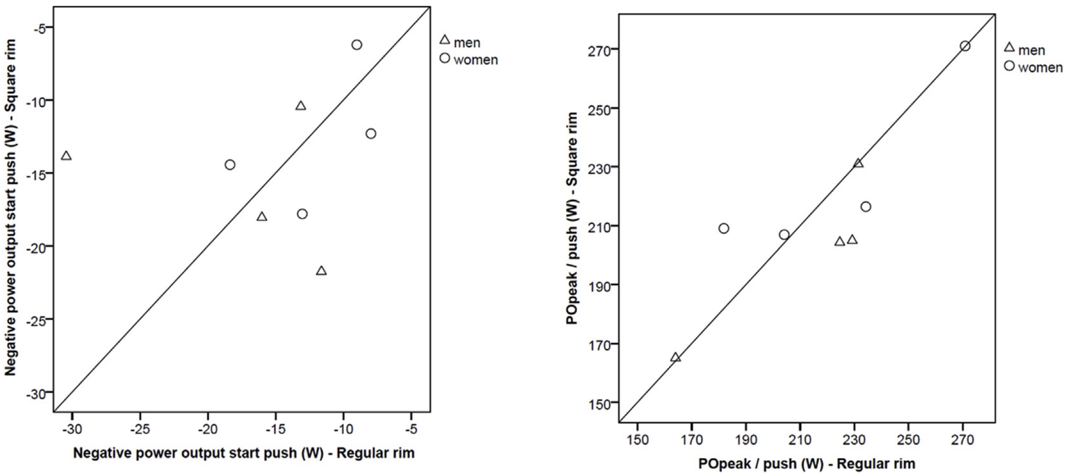


Fig. 4. Individual results of the negative power output at the start of the push (left graph) and peak power output (POpeak) during the push phase (right graph) during exercise block 3 (0.25 W/kg *with* racket) performed with the regular rim (x-axis) and the square-profile rim (y-axis). Each dot represents the outcome of one participant. The diagonal line is the line of identity. For example, if a data point lies above the line in the left graph, this means that the negative power output at the start of the push phase is lower in the square-profile rim condition.

lower percentage push time, lower max speed during the push, and shorter travelled distance.

No significant difference (regular: 2.6 ± 0.7; square: 2.3 ± 1.0; p = 0.40) in grip was found between the rim conditions. However, a trend was seen in the RPE score with the square-profile rim (4.8 ± 1.0) showing a slightly higher score than the regular rim (4.4 ± 1.1; p = 0.08).

4. Discussion

The results showed no significant differences in propulsion technique between the regular and square-profile hand rim when propelling at a submaximal level. However, under more extreme conditions such as sprinting, when using the square-profile rim a lower speed was achieved together with a lower maximal acceleration and lower push frequency. These results were in contradiction with our expectations.

This is the first study where a different rim profile is tested specifically for wheelchair tennis, i.e., when propelling with a racket in the hand. The assumption was that it is easier to hold the racket against a square-profile rim due to the flat and larger surface of the rim instead of the round shape of the regular rim. We expected that wheelchair tennis players would position the racket on either the horizontal or vertical plane of the square-profile hand rim. This might lead to less power loss during (de-)coupling of the racket hand, which was found in a previous study when propelling the wheelchair while holding a racket (de Groot et al., 2017). However, the present study showed that the square-profile hand rim did not diminish the power losses during (de-)coupling when propelling with or without a racket in the hand.

During the sprint test, when propulsion technique becomes more critical, differences were found between the rims but in favor of the regular rim. This might be explained by the fact that the wheelchair tennis players had much more experience with the regular hand rim compared to the square-profile rim. Although they had some practice with the square-profile rim, in terms of minutes, this practice time

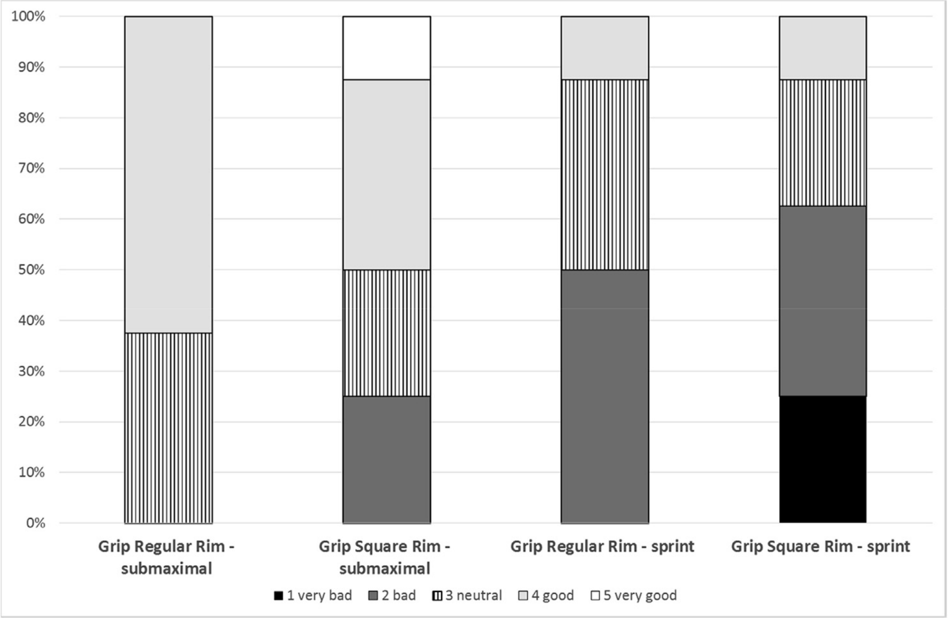


Fig. 5. Distribution of answers given after each rim (regular and square) and exercise (submaximal or sprint) condition regarding how the wheelchair tennis player experienced the tested rim during the specific test (N = 8).

Table 3

Mean (standard deviation) of the propulsion technique variables for the different sprint conditions (with and without racket, regular and square profile) on the right side of eight experienced wheelchair tennis players.

Propulsion technique	Sprints without racket				Sprints with racket			
	Regular, without racket	Square, without racket	p-value Regular vs. Square, without racket	Effect size d	Regular with racket	Square, with racket	p-value Regular vs. Square, with racket	Effect size d
Frequency (pushes/min)	142 (22)	153 (29)	0.409	−0.31	150 (22)	131 (19)	0.073	0.75
Push time (s)	0.17 (0.02)	0.16 (0.02)	0.627	0.18	0.14 (0.01)	0.15 (0.02)	0.161	−0.55
Cycle time (s)	0.44 (0.07)	0.42 (0.06)	0.438	0.29	0.43 (0.06)	0.48 (0.06)	0.076	−0.74
%Push time (%)	38.0 (3.6)	39.4 (2.2)	0.321	0.38	34.5 (3.2)	32.3 (2.8)	0.073	0.74
Contact angle (°)	102 (15)	102 (14)	0.939	0.03	82 (6)	81 (10)	0.695	0.14
POmean/push (W)	514 (153)	512 (156)	0.872	0.06	467 (180)	444 (133)	0.271	0.42
POpeak/push (W)	987 (299)	988 (314)	0.986	0.006	924 (373)	872 (288)	0.178	0.53
Work/push (J)	92.5 (25.3)	90.6 (21.0)	0.388	0.33	73.6 (27.0)	73.6 (21.6)	0.994	0.003
Negative PO start push (W)	−96.9 (46.7)	−116.5 (87.3)	0.410	0.31	−176.3 (74.5)	−172.0 (66.9)	0.823	−0.08
Negative PO end push (W)	−124.1 (33.6)	−149.7 (80.3)	0.280	0.41	−121.1 (73.0)	−108.9 (46.0)	0.267	−0.43
Mean overall speed (m/s)	10.6 (0.9)	10.7 (0.7)	0.547	0.22	9.8 (1.1)	9.1 (0.8)	0.043	0.87
Mean overall PO (m/s)	195.5 (55.0)	202.8 (54.4)	0.621	−0.18	152.4 (62.5)	134.3 (29.3)	0.201	0.50
Travelled distance (m)	17.6 (1.6)	17.6 (1.5)	0.876	−0.06	16.3 (1.8)	15.1 (1.2)	0.067	0.76
Max speed (km/h)	12.3 (0.9)	12.3 (0.6)	0.768	0.11	11.4 (1.3)	10.5 (0.9)	0.026	1.00
Max speed push (km/h)	10.9 (1.0)	11.1 (0.7)	0.466	−0.27	10.1 (1.1)	9.4 (0.8)	0.053	0.82
Max acceleration (m/s^2)	18.1 (2.6)	12.5 (1.8)	< 0.001	3.31	18.6 (5.2)	10.9 (1.2)	0.006	1.38
Max PO (W)	1251 (278)	1338 (417)	0.387	0.33	1210 (522)	1125 (360)	0.318	0.38

might not have been long enough. The coupling of the hand in combination with the racket might be a more training-dependent skill that these athletes acquire over a much longer timescale of practice than originally expected (Newell et al., 2001). Although a longer adaptation phase might have improved the performance of the wheelchair athletes, a very long adaptation phase (in terms of weeks or months) is not doable in these tennis players when they are not yet convinced that the new rim is better. Another option would have been to include able-bodied participants without experience with any of the two rims. However, as previous research pointed out (de Groot et al., 2003; Vegter et al., 2014), a learning effect will definitely take place because they are not used to wheelchair propulsion in general, let alone with a racket in their hand. In the future, a randomized-controlled trial to investigate two able-bodied groups that learn to propel the wheelchair with a racket in their hand and using a standard round rim and a newly developed rim would be very interesting. Future studies on hand rim design could also look at the initial motor learning phase of novice wheelchair tennis players for proper individual optimization while this skill is still flexible and being learned.

To check how well the athletes were able to couple hand and racket to the new hand rim the video recordings were reviewed that were made during the tests. When viewing the video recordings, it was seen that not all players placed the racket exactly on the vertical or horizontal plane but some placed the racket on the intersection of both planes. Of course, this might have had an effect on the results. Furthermore, for development of a new rim design the differences in placement of the racket on the rim among the players should be taken into account. Subsequently the question is whether there should be one rim design, which is most effective from a biomechanically viewpoint, or more rim designs to fit each kind of placement of the racket on the rim, e.g., on top, on the side and on the intersection of both planes of the rim. Actually, it is rather strange that athletes with all kinds of body sizes play with the same general purpose hand rim and racket handgrip diameter. It might well be that individual cases benefit from the square-shape design even if no group effect was found. Differences between individuals regarding propulsion technique outcomes and experienced grip when the regular rim is compared to the square-profile rim are visualized in Figs. 4 and 5. These figures show that while some wheelchair tennis players showed a deterioration in propulsion technique or experienced the grip as very bad when using the square-profile rim, others showed comparable results between hand rims or favorable results for the square-profile rim.

With that in mind, a multiple of design options are available besides the shape of the hand rim, like the texture and material of the rim. Previous studies showed interesting results with respect to redesigning the hand rim (Koontz et al., 2006; Richter et al., 2009; Van der Linden et al., 1996), especially when looking at the grip. It was suggested that a larger rim diameter led to a better grip and subsequently less stabilization by the larger muscle groups (Van der Linden et al., 1996). The diameter of the NaturalFit rim is similar to the regular rim in the horizontal direction but twice as large in the vertical direction. Furthermore, the rim has a higher-friction contoured slot for the thumb between the hand rim and the wheel rim. The NaturalFit showed reduced grip moments during the slow speed condition but the peak resultant forces were higher during a fast speed (Koontz et al., 2006). Lastly, the FlexRim, has a regular rim but also has a high-friction elastic membrane between hand rim and wheel rim, which led to reductions in both peak and total forearm muscle activation (Richter et al., 2006) and oxygen costs (Richter et al., 2009). In wheelchair tennis both propulsion and braking are important due to the many short sprints and turns. A different rim profile should focus on better supporting the hand with racket. A higher rim friction might lead to a better propulsion performance but might be unsuitable when maneuvering and braking. So, the focus should also be on the specific place of the higher friction on the rim. Besides these issues the material of the rim is important with respect to, for example, weight, rigidness, and temperature regulation.

Determining these design parameters, by e.g. detailed analyses of racket placement on the rim in wheelchair tennis (by video analysis), interviews with, among others, wheelchair tennis players, literature research, and studying effects of material and texture, is necessary to define a new hand rim design for wheelchair tennis. Based on the results of our previous study (de Groot et al., 2017) and the present study, we have started a project to design a new hand rim for wheelchair tennis (Koopman et al., 2016). The major modification of this rim design will be a different surface to have a more stable position of the racket on the rim. The expectation was that the square-profile rim would have this advantage but this was not shown in our results. The shape of the rim should be adapted better to the way the player has the racket in his hand and how he couples the hand with racket to the rim.

Our study has some limitations. One of the limitations is the practice time, which might have had an effect on the results as described above. Furthermore, a stationary wheelchair ergometer was used for testing, which has a different set-up, albeit individually adjusted, compared to the player's own wheelchair and does not require steering, yet is similar as used in the study of De Groot et al. (de Groot et al., 2017). However, with this ergometer we were able to measure the propulsion technique under standardized conditions and, therefore, able to compare the results of the two rim conditions. It is recommended for future studies to test wheelchair tennis players in their own wheelchair on, e.g., an ergometer with a roller system and test specific wheelchair tennis skills to include the performance during maneuvering as well. Lastly, eight participants is not a very large sample. However, since we included real wheelchair tennis players, it is almost impossible to have a much larger sample size. Besides that, our previous study on the effect of holding a racket on a propulsion technique of wheelchair tennis players (de Groot et al., 2017) was also performed with eight participants and found very clear differences in propulsion technique between propelling the wheelchair with and without a racket in the hand.

5. Conclusions

This study showed that a square-profile hand rim does not seem to improve the propulsion technique, i.e., among others, diminish the power loss during (de-)coupling, when propelling a wheelchair with a tennis racket in the hand compared to a regular rim after a short practice time. Therefore, currently no clear advantage of the new hand rim can be established based on these results. However, the results gave input for new hand rim designs for wheelchair tennis and emphasized the need for longer training sessions to optimize the skills for the specific design.

Conflicts of interest

None.

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