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RESEARCH ARTICLE

A comparison of vertical reaction forces during propulsion of three different one-arm drive wheelchairs by hemiplegic users

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Abstract

Purpose: The aim of this pilot study was to compare the vertical reaction forces (*N*) generated in three different Action 3 manual one-arm drive wheelchairs: dual handrim, a lever drive and a Neater Uni-wheelchair (NUW). A CONFORmat® Pressure measurement mat, placed on top of the users' prescribed cushion, measured vertical force at the buttock/seat interface on both hemiplegic and non-hemiplegic sides in each wheelchair. *Methods*: Fifteen hemiplegic users were randomly assigned each wheelchair to drive around an indoor obstacle course. During propulsion of a multiple sensor, continuous measurement of force was recorded. Time taken to complete the circuit was recorded. Mean force and confidence intervals for each buttock were calculated per user per wheelchair. *Results*: The dual handrim produced the highest vertical force during propulsion under the right buttock ($\bar{x} = 484.43$; SD $= 55.4$; $p < 0.001$) and the lever drive produced the least force ($\bar{x} = 368.05$; SD $= 53.55$; $p < 0.01$). The NUW completed the course quickest ($p < 0.01$). *Conclusions*: The dual-handrim wheelchair requires the greatest vertical force during propulsion. Since increases in this seat vertical reaction force may be related to the propulsive force. Further investigation is indicated as this may be a significant factor for clinicians when prescribing one-arm drive wheelchairs.

Keywords

Assistive technology, force measurement, propulsion

History

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➤ Implications for Rehabilitation

- Review of clinical reasoning in prescribing wheelchairs.
- Addition of the Neater Uni-wheelchair to wheelchair services prescribing lists.

Introduction

The standard manual wheelchair is an effective, but inefficient means of transport [1]. Mandy et al. [2] summarised the literature regarding wheelchair provision for hemiplegic subjects, and identified a lack of suitable provision. Kirby et al. [3] specifically identified the difficulties faced by hemiplegic wheelchair users and further suggested that improvements were needed in wheelchair provision for this group. Hemiplegic users face cognitive, perceptual and physical difficulties. Although the cognitive and perceptual difficulties are difficult to address, the physical difficulties can be ameliorated by improvements in wheelchair design. Current provision includes two different types of propulsion: the ratchet arm or lever-drive mechanism and the dual-handrim mechanism. Lever arm design, such as the NuDrive (Watford, Hertfordshire, UK) or Pivot (Pivot Rio Mobility, San Francisco, CA), involves a pushing or pulling action on the end of a lever mechanism [3,4]. The second type of design is the dual handrim where the two handrims are mounted on the same side of the wheelchair. Propulsion involves gripping and rotating both rims at the same time in order to move forward in a straight line. This can be difficult for users with a small hand span or with impaired hand function. Alternatively each rim may be used in turn to propel the wheelchair forwards but this can result in a snake-like movement, which is inefficient and requires significant effort. Contemporary versions of this propulsive mechanism include the Nomad (Nomad Lampeter, Wales, UK) and Invacare Action 3 (Bridgend, UK). However, there are deficiencies associated with both of these designs particularly with respect to the user interface. The lever drive design usually has a fixed mechanical advantage, the ergonomics of simultaneous propulsion and steering can be awkward and the operation of the brake is not intuitive. In the dual-handrim designs, steering and propulsion cannot be actuated simultaneously. Braking via the dual handrims is more difficult than with a standard wheelchair because the user must simultaneously grasp both handrims to avoid turning. For a large number of users, the overall ergonomics of operation are not efficient. Literature reports that nearly 70% of wheelchair users experience upper extremity pain or overuse injury at some point [5,6]. Anecdotally, clinicians report that the current one-arm drive wheelchairs do not meet the needs of hemiplegic users, which may explain the high level of wheelchair abandonment. Wheelchairs have the highest level of abandonment, more than any other mobility device [7–9]. Moreover, high-abandonment rates leave many individuals without the technology they need and may in turn results in users resorting to inappropriate devices [7]. In the case of

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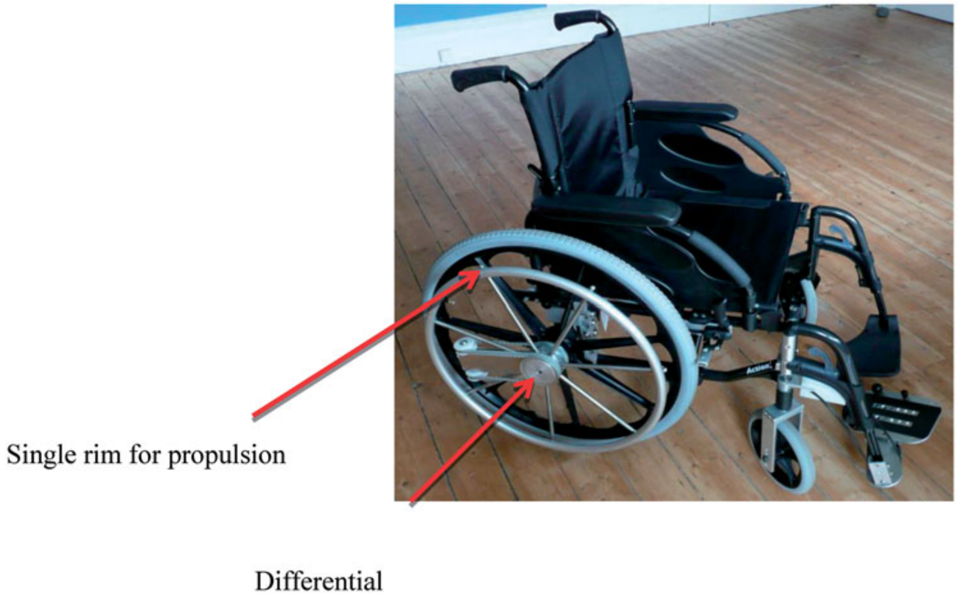

Figure 1. The NUW Kit attached to an Action 3 wheelchair.

Figure 2. The steering mechanism.

wheelchair users, this is commonly the standard issue to use wheelchairs in which clinicians, anecdotally, report that users propel through punting (the use of the non-disabled leg to move the wheelchair forward) or become reliant on others to propel them. This hemiplegic pattern has been described by Kirby et al. [3], who concurred with the difficulties identified when propelling a standard wheelchair.

In response to this problem, Mandy et al. [2] and Mandy and Lesley [10] have developed an alternative one-arm drive wheelchair, the Neater Uni-wheelchair (NUW) (Buxton, UK). The NUW is an Action 3 wheelchair to which a novel propulsion and a steering kit is attached. Both these features have been described in detail in an earlier paper by Mandy and Lesley [10]. The NUW was designed by clinicians, users and engineers for hemiplegic users with only the use of one arm and one leg. The novel combination of the differential and a self-propulsive steering mechanism kit enables the user to steer with the footplate, and propel the wheelchair with only one handrim. Thus, the user is able to propel and steer simultaneously with no interference between the footplate and the castor. In addition, the kits can be attached to either side for use by either right-handed or left-handed users (Figures 1 and 2). The research by Mandy et al. [2] and Mandy and Lesley [10] to date has compared the NUW with the Invacare Action 3 dual handrim, and the findings suggest that the NUW is ergonomically more efficient to drive and preferred by users in both a laboratory setting [2,10] and the activities of daily living setting [11]. A further study evaluated users' experience of using the NUW in their own homes [12]. Four key themes of increased user independence and freedom, ease of use and manoeuvrability, usefulness and increase in activity were reported [12]. These studies suggested that NUW could meet the unmet needs of the hemiplegic user group and provide them with additional choice in their wheelchair provision. The research also advocated that the NUW to be viable alternative to the current catalogue of one-arm drive wheelchairs available to rehabilitation therapists. Although their earlier research measured expired gases and heart rate to evaluate energy usage and efficiency [10], there has not been any research to measure the forces generated while propelling different one-arm drive wheelchairs. Changes in force under the buttocks could be considered to be the changes in reaction forces caused by the forces applied through the hands to propel the wheelchair [13,14].

As such a greater propulsion force would result in a greater change in reaction force. Therefore, measurement of reaction force at the seat interface may give an indication of the forces required for propulsion. The measurement of force at the buttock/seat interface is complicated because the tool must be flexible and able to conform to the contours of the buttocks. There are many systems for measuring contact pressure of which the CONFORMat® (Tekscan Conformat, Boston, MA) is a recognised tool and has been widely used in the study of pressure sore management [15–17]. The CONFORMat® also has an inherent correction for creep which is made during the calibration process [17]. Although the CONFORMat® is marketed as a tool for measuring pressure, the data measured are those of force which are then converted into pressure by dividing the area of each sensor. Pressure was not considered as an appropriate measure in this study because of the influence of changes in the contact area on the absolute values of the data collected. Force between the buttock and the seat is a novel measurement in wheelchair studies and will give an indication of the effort required for propulsion.

The aim of this study was to compare vertical reaction force generated at the buttock/seat interface whilst seated in three different one-arm drive wheelchairs during propulsion. The research hypothesis was: there will be differences in vertical forces at the seat/buttock interface when propelling different one-arm drive wheelchairs.

Methods

Ethical approval was sought and obtained from the University of Brighton Research Ethics committee and also from the North Wales Research Ethics Committee prior to commencing the study. Research Governance approval from Betsi Cadwaladr University Health Board was also sought and obtained for the study.

Potential participants were identified by the head occupational therapists from the data base of patients at The Posture and Mobility Service. The search identified hemiplegic users who were one-arm wheelchair drivers with at least 1 year experience. Twenty potential users were identified and screened by the rehabilitation team suitable for including into the study. Of these, 15 users were agreed to participate in the study.

Recruitment and screening

The inclusion criteria were as follows: deemed able to consent by the Posture & Mobility Service rehabilitation team, willingness to participate and hemiplegic experienced one-arm drive wheelchair users. The exclusion criteria were as follows: musculoskeletal pain or injury to the non-hemiplegic upper limb, unstable medical conditions, cognitive or perceptual difficulties, height and weight restrictions of 163–185 cm and 54–90 kg, respectively. All subjects who wished to participate completed a health declaration sheet and informed consent sheet.

The study was designed as a controlled, same-subject study that measured the force generated by each user during propulsion in three different one-arm drive wheelchairs.

The data being measured were vertical reaction forces at the buttock/seat interface in Newtons. These were measured using the CONFORMat® Pressure Measurement System, a portable interface pressure mapping system, which records pressure distribution under the contact area. The system includes pressure-sensing hardware and software. CONFORMat® is an instrumented mat of approximately 0.5 m^2 containing 1024 sensors which sample direct loading at 10 Hz. The CONFORmat® software version 6.20 was used to record and process the data. The system was calibrated for each subject prior to data collection as recommended by the manufacturer [17].

The study was conducted at an indoor circuit at the Artificial Limb and Appliance Centre in Wrexham (Figure 3). All participants were given familiarisation training in the use of all the wheelchairs until they felt competent to undertake the trial. Propulsion of the dual-handrim wheelchair required the user to grasp and compress both handrims together to propel in a straight line and grasp the individual handrims alternately when steering and manoeuvring. When manoeuvring the NUW, the users grasped the single handrim for propulsion and the foot steering plate for directional control. Propelling the lever wheelchair involved flexion and extension of the shoulder and a forward and a backward motion. Steering occurred by rotating the lever handle, using abduction and adduction of the wrist.

The participants familiarised themselves with the indoor circuit which consisted of manoeuvring along a carpet-covered corridor, through a door jamb, around a circular course of obstacles and then returning back down the corridor to the start. The course included both right-hand and left-hand turns. Subjects were randomly allocated the wheelchairs using random numbers.

Procedure

Demographic data including age, gender and side of impairment were recorded for all subjects. Prior to commencing the course, the CONFORMat® was placed on the users' own pressure cushion which was then placed in turn in each of the wheelchairs. The participant was positioned in a symmetrical sitting posture in each wheelchair and initial data capture was undertaken in this static position prior to driving each wheelchair around the course. The participants were asked to drive the wheelchair round the course at their own speed. Data were captured continuously throughout each circuit. The system was calibrated for each participant per wheelchair using the standard calibration process as recommended by the manufacturer [17]. The course was repeated once per wheelchair with a 30-min gap, or however, much time was necessary, for the users to feel recovered. Refreshments and comfort breaks were available at all times.

Data processing

The raw force data were manipulated using the CONFORMat® software to generate a right and left field which represented each buttock. A mean value for each buttock was calculated for the duration of propelling the wheelchair around the indoor circuit.

Statistical analysis

The study was designed to compare the measurements taken in each wheelchair for each individual participant, with each user acting as their own control. This was considered to be an appropriate approach due to the heterogeneity of hemiplegia within the user group and the bespoke postural and pressure equipment that they used in the wheelchairs during the study. The mean and 95% confidence interval for each participant in each wheelchair were calculated and used to determine statistically significant differences in vertical forces. The data for the user group are described in Table 1.

The data were also investigated to explore differences in vertical forces between wheelchairs across the whole sample. The data were tested for normal distribution using the Anderson Darling Test and found to be normally distributed. Differences between forces under each buttock across all wheelchairs were explored using a one-way analysis of variance (ANOVA) with Tukey's *post hoc* test.

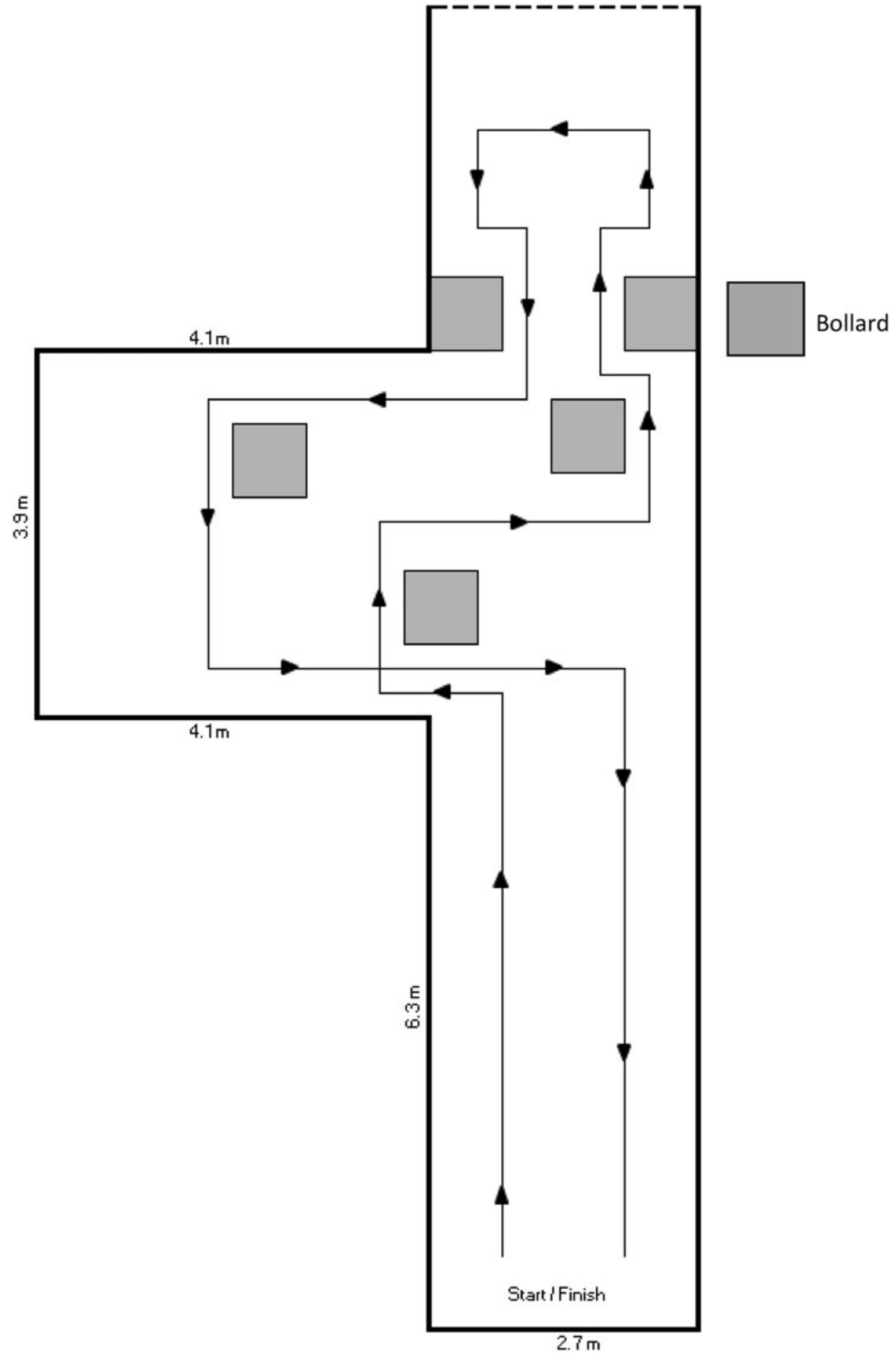

Figure 3. Map of the indoor circuit.

Vertical forces were compared within each wheelchair to investigate the symmetry of loading between buttocks using *t*-tests. Time taken to complete the circuit was compared using a one-way ANOVA.

Results

Gender distribution: six women and nine men

All participants had left-sided hemiplegia of at least 1 year duration with no cognitive or perceptual difficulties.

The vertical force data from each participant for each wheelchair are expressed as confidence intervals, and are shown in Table 2. The data were considered for the right and left buttock separately. Forces generated when using each wheelchair were compared. When there is no overlap in the confidence intervals, then there is an indication that the measured vertical forces are

Table 1. Mean and range of age of the participants.

	All	Male	Female
Mean (SD)	56.6 (17.1)	55.3 (19.3)	58.5 (14.8)
Minimum	24	24	32
Maximum	83	83	78
Range	59	59	46

Table 2. Mean and 95% confidence intervals of force (*N*) for each user in each wheelchair.

	Right side			Left (hemiplegic side)		
Participant no.	Neater	Lever	Dual	Neater	Lever	Dual
1	443.12 (439,446)	285.7 (283,287)	500.43 (495,505)	338.52 (336,340)	349.17 (346,351)	335.87 (333,338)
2	417.25 (414,420)	397.59 (395,399)	543.7 (539,547)	339.53 (2337,342)	304.31 (302,305)	348.14 (345,351)
3	395.74 (393,397)	413.41 (411,415)	454.4 (450,457)	356.33 (354,357)	335.08 (334,336)	363.83 (362,365)
4[a]	–	–	–	–	–	–
5	435.55 (431,439)	431.44 (429,433)	383.77 (380,387)	352.33 (350,353)	386.35 (384,387)	375.03 (373,376)
6	332.32 (329,335)	335.6 (333,337)	484.2 (477,490)	313.17 (312,314)	312.56 (310,314)	237.42 (234,240)
7	523.77 (519,527)	340.05 (337,342)	596.05 (591,600)	402.02 (400,403)	444.27 (442,446)	468.08 (465,470)
8	452.79 (449,456)	394.16 (391,396)	517.18 (512,521)	281.75 (280,283)	296.98 (295,298)	370.24 (367,372)
9	387.86 (482,489)	485.93 (480,487)	428.96 (586,596)	404.30 (385,390)	418.75 (426,431)	591.53 (416,420)
10	451.35 (448,454)	346.96 (344,349)	519.14 (513,524)	566.85 (565,568)	454.88 (452,456)	466.71 (463,469)
11	518.49 (515,521)	348.02 (346,349)	524.43 (521,527)	404.71 (403,406)	464.52 (463,465)	542.7 (540,544)
12	374.26 (371,377)	336.08 (334,337)	463.74 (461,466)	341.89 (340,342)	377.92 (377,378)	378.42 (377,379)
13	415.42 (412,418)	298.51 (296,300)	443.81 (440,446)	300.02 (299,300)	301.04 (300,302)	295.39 (293,297)
14	482.72 (479,486)	355.09 (353,357)	513.22 (509,516)	331.52 (329,333)	337.21 (335,338)	454.87 (452,456)
15	472.51 (468,476)	384.2 (382,385)	549.01 (544,553)	350.12 (348,351)	380.59 (379,382)	440.69 (438,443)
Mean	435.94	368.05	494.43	363.08	368.83	404.92
SD	53.97	53.55	55.40	69.33	58.76	95.24

[a] Data were corrupted.

Table 3. Least force of right and left sides generated at the patient/wheelchair interface in each wheelchair.

	Least force on right side			Least force on left (hemiplegic) side		
Participant no.	Neater versus lever	Neater versus dual	Dual versus lever	Neater versus lever	Neater versus dual	Dual versus lever
1	L	N	L	N	ns	D
2	L	N	L	L	N	L
3	N	N	L	L	N	L
4[a]	–	–	–	–	–	–
5	L	N	L	N	N	D
6	N	N	L	ns	D	D
7	L	N	L	N	N	L
8	L	N	L	N	N	L
9	N	N	D	N	N	L
10	L	N	L	L	D	L
11	L	N	L	N	N	L
12	L	N	L	N	N	Ns
13	L	N	L	ns	D	D
14	L	N	L	N	N	L
15	L	N	L	N	N	L

[a] Data were corrupted. L, lever; D, dual; N, Neater; ns, non-significant difference.

statistically different ($p < 0.05$). A summary of the statistical differences is shown in Table 3.

Comparison of the mean force values from the whole sample (Table 2) demonstrated a significant difference between force exerted under the right (non-hemiplegic) buttock across all three wheelchairs [$F(2,39) = 18.98$, $p < 0.001$]. *Post hoc* comparisons using the Tukey HSD test indicated that the mean forces for the dual handrim ($\bar{x} = 494.43$, SD = 55.40) were significantly higher than that for the lever ($\bar{x} = 368.05$, SD = 53.55) and the Neater ($\bar{x} = 435.93$, SD = 53.97).

The analysis of the forces (*N*) under the left (hemiplegic) buttock showed no significant differences between the three different wheelchairs.

Vertical forces for each buttock in each wheelchair were compared to explore symmetry using *t*-tests. There was a significant difference in forces exerted by the non-hemiplegic and hemiplegic buttocks in the NUW ($t = 3.605$, $p < 0.005$) and also the dual-handrim wheelchair ($t = 3.295$, $p < 0.01$). In both cases, the non-hemiplegic side had higher measured force than the hemiplegic side. There was no significant difference between the buttocks when using the lever wheelchair.

The mean time (s) taken to complete the circuit was also statistically compared using a one-way ANOVA. The mean values were found to be: 81, 86 and 130 s for NUW, lever and dual handrim, respectively. The NUW and lever were significantly faster than the dual handrim [$F(2,39) = 21.21$, $p < 0.001$]. There was no significant difference between the NUW and lever wheelchair.

Discussion

The aim of this study was to measure and compare the vertical reaction force generated during propulsion, at the buttock/seat interface, in a sample of left-sided hemiplegic wheelchair participants. The objective of the study was to identify which one-armed wheelchair generated the least vertical reaction force when manoeuvring in a controlled environment around obstacles.

The results were explored for both the hemiplegic and non-hemiplegic sides independently. On the non-hemiplegic side, the results indicated that the lever wheelchair required the least vertical reaction force during the propulsion and that the dual-handrim wheelchair required the greatest force. The NUW required less force than the dual handrim but more force than the lever wheelchair. For the hemiplegic side, the NUW required less force for the propulsion than either of the other two wheelchairs and the dual handrim again produced the greatest force.

The results indicate that the dual-handrim wheelchair required the user to produce the greatest forces under both sides of the body for propulsion. Therefore, these results suggest that the dual-handrim wheelchair is the most inefficient of the three, which concurs with the earlier work of Mandy et al. [2] and Mandy and Lesley [10], who compared the physiological efficiency of the NUW to the dual handrim.

Comparison of the forces applied beneath the right and left buttocks gives rise to data which could be interpreted in various ways. The force measured through the non-hemiplegic side was greater in both the Neater Uni- and the dual-handrim wheelchairs.

A possible explanation of this is that changes to postural position occurred during propulsion resulting in the participants becoming seated in an asymmetrical position. Although this cannot be determined from the data generated in this study, further work exploring changes in the centre of force would demonstrate any changes in the symmetry of the seated position. The current data might suggest that in the NUW, the user's position has moved towards the non-hemiplegic side. It has been established that asymmetric posture leaning towards the non-hemiplegic side is common in one-arm propulsive wheelchairs [7] and is seen clinically as a disadvantage to the users. Although there was no visible change in the position, there may have been subtle differences that were recorded by the CONFORMat pressure mat. Conversely, it is possible that differences in modes of propelling the wheelchairs may have led to selective loading on one side of the body which in turn would explain the differences in force exerted. To explore this, further recording of changes in the centre of force during such an activity would enable this question to be answered. Such data would indicate whether the changes were transient or sustained which in turn would confirm a change in sitting posture.

The time taken to traverse the course was also significantly faster in the NUW and lever wheelchair than in the dual-handrim wheelchair. This result further endorses the work of Mandy et al. [2] and Mandy and Lesley [10] in which the NUW was shown to be the most efficient. Later work by Mandy et al. [12] also confirmed users' preference in manoeuvring the NUW because of its ease of use.

Conclusion

This pilot study of hemiplegic users suggests that the dual-handrim wheelchair requires more force for the propulsion compared with the lever and the NUW. Further work is indicated to explore changes in posture, and propulsive effort in the NUW and lever wheelchairs. Rehabilitation teams may wish to review their clinical reasoning in relation to prescribing wheelchairs for hemiplegic users on the evidence presented.

Declaration of interest

There is no conflict of interest between the participating parties. All contributors have reviewed and agreed the content of the manuscript.

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