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ON THE DESIGN OF DEVICES FOR PEOPLE WITH TETRAPLEGIA

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ABSTRACT

People with complete tetraplegia are required to work at or near their physical limits in performing daily activities. Hence, subtle improvements to the design of assistive devices can have life changing consequences. This paper establishes a new procedure for characterizing the strength of people with tetraplegia. The data obtained along with the specifications of assistive devices are implemented in the Bath Constraint Modeller and then predictions made of a subjects ability to use the assistive device. This paper shows how improvements in wheelchair propulsion ability can be made within the constraints of normal wheelchair adjustment. From the characteristic strength maps produced in this study, it is predicted that more marked improvements can be obtained by changing the position of the applied propulsion force. The study proposes a new design concept involving an offset push rim which is expected to improve wheelchair propulsion ability for people with tetraplegia. More generally, the results of this study pose new opportunities for improvements to assistive devices for people while seated.

Keywords: design of assistive devices, tetraplegia, human strength

1. INTRODUCTION

People with Spinal Cord Injuries (SCI's) face a daily struggle with everyday tasks. For many, independent living is an unrealistic expectation. The most common level of SCI [1] is in the cervical spine. A complete break in the spinal cord at the cervical level results in total paralysis from the neck down. The upper limbs have varying degrees of motor and sensory function depending on the exact location of the injury in relation to the cervical nerves.

Each year a significant number of people are affected by SCI's. For example, the annual incidence spinal cord injury in the United States is approximately 40 per million population, equating to 12,000 new cases per year [2]. Estimates of the total prevalence of SCI's in the US have ranged from 127 080 to 300 938 persons. Tetraplegia has constituted 52.4% of all new SCI's since 2000, with 34.1% of new SCI's incomplete tetraplegia and 18.3% complete tetraplegia.

Surgical procedures have been evolved to improve quality of life and independence for people with SCI's. One of authors has performed or supervised around 100 posterior deltoid to triceps transfer (TROIDS) procedures. One of the benefits of this surgery is that it improves a person's ability to perform basic activities such as feeding themselves, brushing teeth as well as manual wheelchair propulsion [3]. A benefit of this study is that it provides both a visual and quantitative measure of human strength in the sagital plane. The method can also be used to demonstrate the effectiveness of the surgical procedures such as TRIODS.

The purpose of this study is to provide information for the design of effective assistive devices for people with tetraplegia. In this paper we establish a procedure for characterising human strength using able bodied subjects and we obtain characteristics for three tetraplegic individuals. This information will be used to help better design and prescribe assistive devices for people with tetraplegia. The differences found will also be used to modify and validate mathematical human movement models for people with disabilities which aid in streamlining the design process. Seven people voluntarily participated in this study, four able bodied and three with tetraplegia, the criteria for the later three was that they had complete SCI.

2. BACKGROUND

Pervious studies have mainly concentrated on the voluntary strength of various upper body articulations, particularly shoulder and elbow articulations within an able bodied population. This study which investigates the upper body strength in the combined articulation task of pushing has previously only been studied over a much coarser grid spacing in one dimension. In one particular study, Kumar [4] performed 2-handed tests from a standing position, at 350mm, 1m and 1.5m above the ground and established that the mid-level height was the strongest position.

There is also little data on the upper-body strengths of people with SCIs mainly due to the difficulty in testing this particular population group. The most comprehensive study of the strength of persons with SCIs on the sagittal plane is that of Das and Forde [5] which measured the seated right handed isometric push-up and push-down arm strength in 24 positions for subjects with C4-T11 SCIs. The study found that the push-up strengths of the candidates were only 30% of that of able bodied forces measured by Hunsicker [6] and the pull down forces were approximately 50%. Das and Forde did not, however, distinguish between candidates with different SCIs and they did not include subjects with higher level tetraplegia.

In this paper we consider individuals with tetraplegia. Each person had a SCI as the result of physical trauma. In each case these injuries affected vertebrae of the cervical spine at different levels resulting in complete paralysis of the lower body and varying degrees of sensory and motor loss to the arms and hands. A summary of the subjects, injury levels and resulting sensory and motor control is given in Table 1.

Table 1. SCI level and function (adapted from Floris et al. [7])

No. Subjects	SCI Level	Sensory and Motor Control
1	Cervical injuries (C5-C6)	• Preservation of shoulder abduction + external rotation • Preservation of elbow flexion + variable wrist extension • Little/no voluntary control of elbow extension • No hand function
1	C6 'TROIDS'	• Limited elbow extension
1	Cervical injuries (C7)	• Elbow extension /Wrist extension • Finger extension, no grasp
4	Able body function	• Participants were told they were unable to use there legs for posture support

In a previous study, Gooch et al [8] investigated the difference in wheelchair propulsion ability between people with various levels of tetraplegia. There were found to be distinctly different wheelchair propulsion characteristics between three groups of people with tetraplegia. The three groups were: people without arm extension ability, people with arm extension ability and people with TROIDS for arm extension. These three groups are represented by the three people with tetraplegia measured in this study.

3. EXPERIMENTAL PROCEDURE AND OBSERVATIONS

Each subject was loaded onto the test rig shown in Figure 1. The wheelchair is anchored to the base platform using four ties so that the central axel of the back wheels is located at a reference datum point in the superior/inferior and anterior/posterior directions.

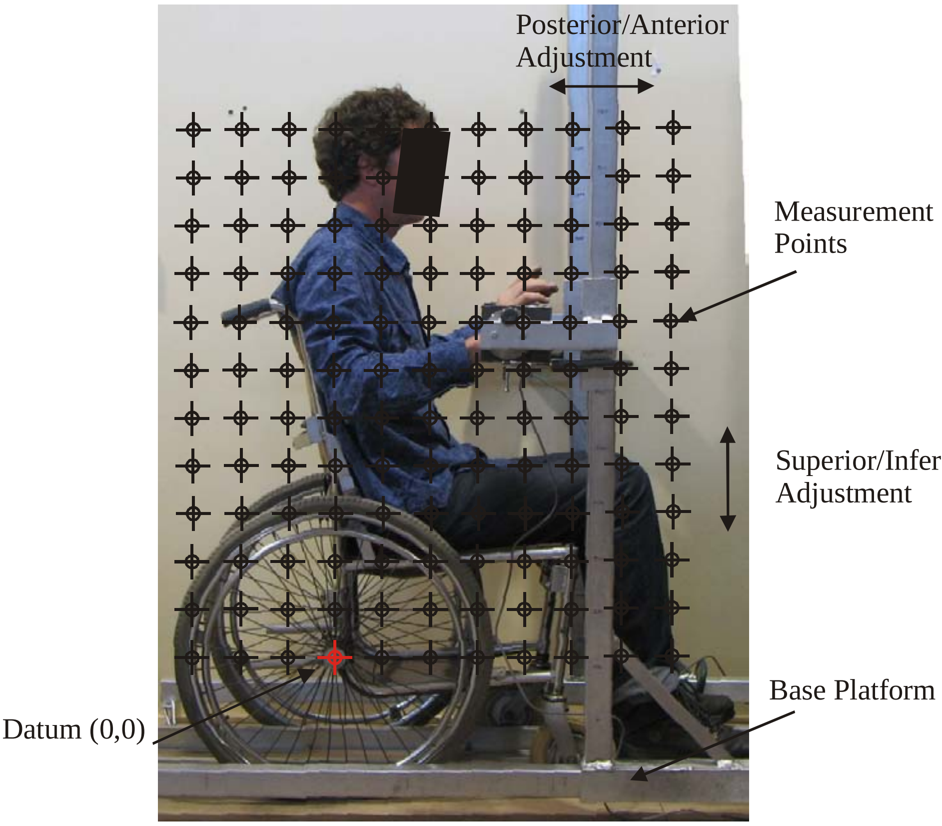

Figure 1. Upper body strength test rig showing measurement points

The subjects horizontal push force is measured using two calibrated LPX-50kg compression load cells, one for each arm, which are fixed to aluminium posts. The position of the applied force can be adjusted in the sagittal plane in the superior/inferior and anterior/posterior directions as indicated in Figure 1. The measurements are recorded over a grid spacing of 100mm. While the subject's strength can be measured at any point and in any direction, the grid positions used for measurements in this study are listed in Table 2.

Table 2. Grid positions for strength test measurements

Direction	**Distance from the centre of the wheel (mm)**											
Anterior/Posterior	-400	-300	-200	-100	0	100	200	300	400	500	600	
Superior/inferior	0	100	200	300	400	500	600	700	800	900	1000	1100

While there are 120 possible grid positions, some positions are physically unreachable depending on the person's flexibility, stature, sensory function and motor control. In each position the subject pushes on the centre of a hemispherical hand support which transfers the force onto the LPX-50kg compression load cell as shown in Figure 2. During the strength test, the subject is free to adopt the posture they think will allow them to produce the maximum push force. Subsequently, the maximum force is recorded and if the position is deemed physically unreachable a force reading of zero is recorded.

At the beginning of the test the frame is positioned so that the hemispherical hand support is at a point close to the centre of the user's range of motion. Once data has been recorded at each vertical position, the post is moved in either the anterior or posterior directions by a distance of at least 200mm and a new set of data captured. This minimum distance is used to help mitigate the effects of fatigue from the prolonged use of one muscle group.

The effect of fatigue is also reduced by allowing the candidate to have sufficient rest between each push measurement. Using the Rohmert fatigue model [9] the recommended rest time necessary to eliminate fatigue with a force application of one second at a maximum voluntary contraction of 0.9 was predicted to be 48.1 seconds. Depending on the difficulty in adjusting the load cells to the new position the approximate rest time between positions was found to be 40 – 60 seconds. The effect of fatigue was checked periodically throughout the testing procedure by moving the vertical posts back to the starting position in anterior/posterior direction and re-measuring. A review of strength-training literature indicates that there is a direct relationship between reps-to-fatigue and the percentage of maximal load. As the percentage of maximal load increases, the number of repetitions decreases in a linear fashion [10]. The average difference in these three repeated measurements can then be used to estimate a percentage loss in strength per repetition. Therefore each recorded strength measurement is multiplied by this loss factor and the number of reps since the commencement of the test to give an equivalent un-fatigued strength measurement. If fatigue is noticed and is consistent in the superior/inferior direction then the effects of fatigue can be considered in the analysis.

Figure 2. Load cell attachment brackets

Force maps were created using the force measurement results obtained from measuring four subjects with normal motor and sensory control. These subjects were 22 to 60 year old males and their force maps are shown in Figure 3. The results obtained for the four people with normal motor and sensory control show that people seated have a maximum forward push force in their lap area.

The results of strength measurements for the subject with C5/C6 tetraplegia are shown in Figure 4. The subject had slightly better motor and sensory control on his left side and a moderate strength region exists around the -200,300 position. From these results it is evident that the subject would be expected to have better wheelchair propulsion ability if his seat height was lowered by approximately 100mm.

The results of strength measurements for the subject with C6 tetraplegia (TROIDS), Figure 5, also illustrate an asymmetric strength profile. This result is consistent with anecdotal evidence suggesting that the subject had a markedly more successful outcome of the TROIDS procedure on his right side than on his left side. Comparing Figures 4 and 5, the C6 (TROIDS) subject is approximately twice as strong as the C5/C6 subject. His strength map indicates more function in the lap area which is consistent with having improved arm extension ability.

The results of strength measurements for the subject with C7 tetraplegia are shown in Figure 6. While the subject with C7 tetraplegia had a similar force map to the people tested with normal arms, his strength was approximately 20% of that measured from the subjects with normal motor and sensory control.

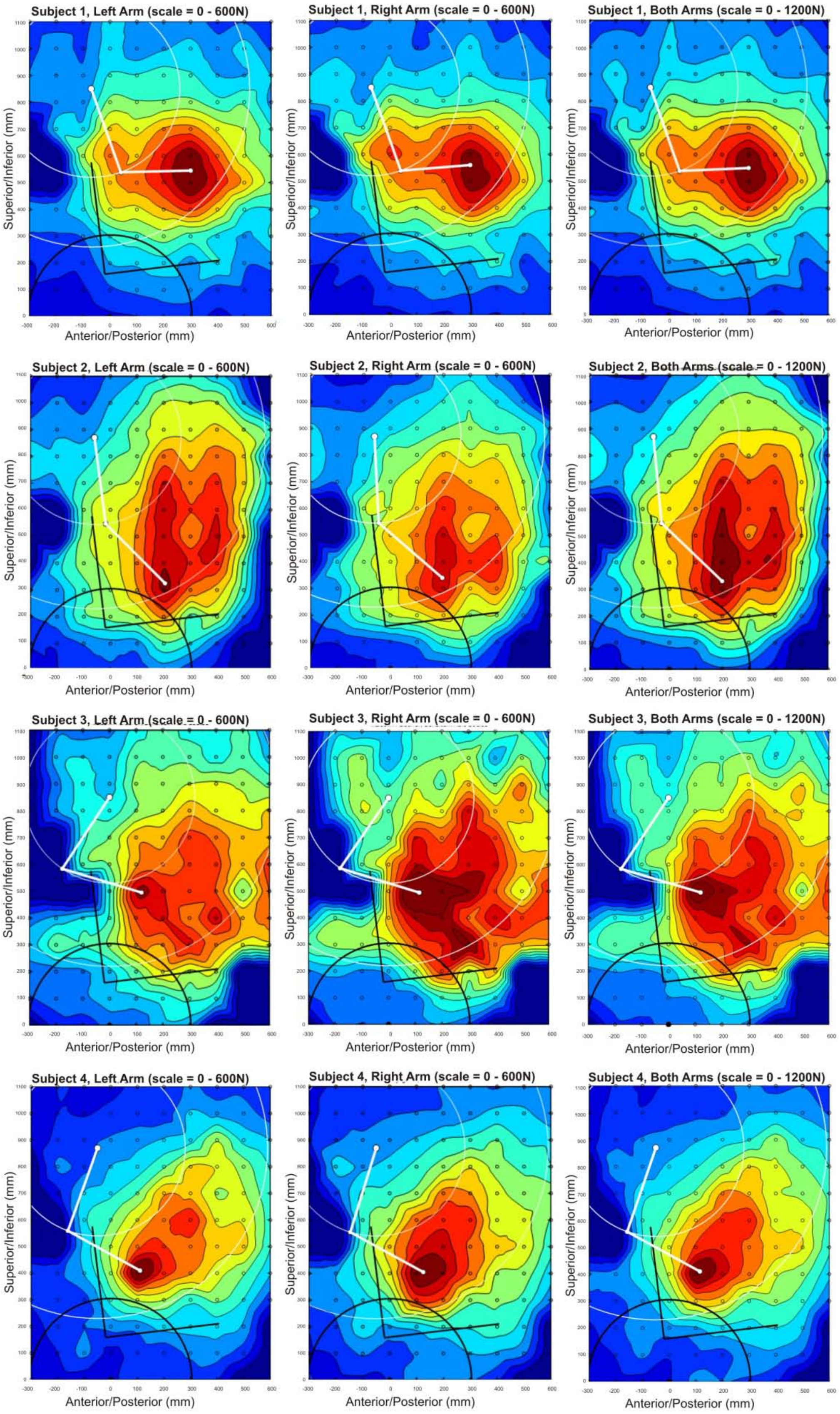

Figure 3. Force maps obtained from measuring four people with normal motor and sensory control.

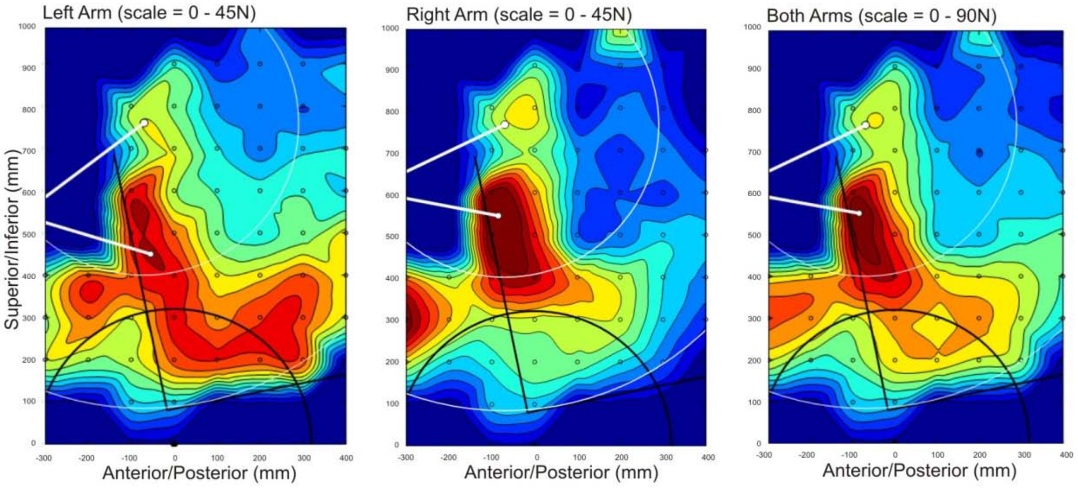

Figure 4. Force maps obtained for the subject with C5/C6 tetraplegia.

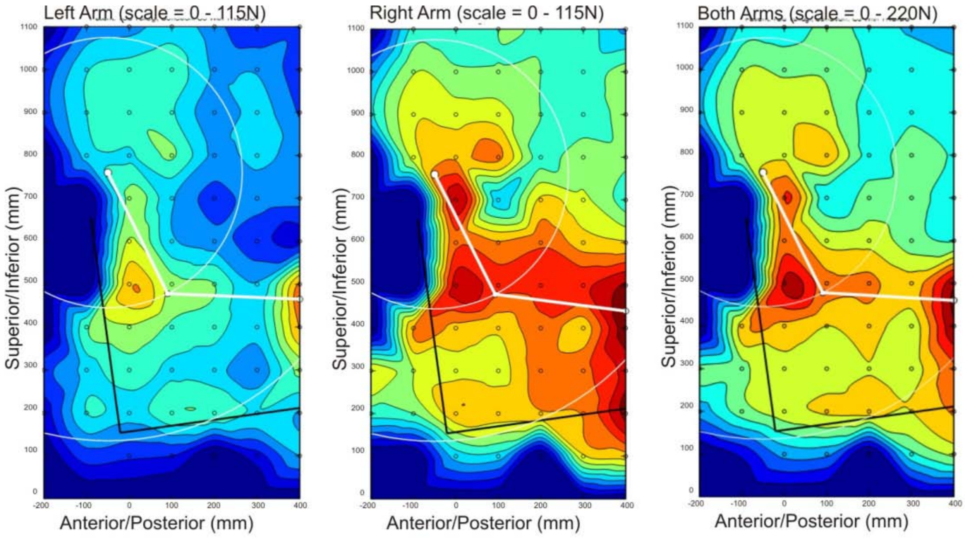

Figure 5. Force maps obtained for the subject with C6 tetraplegia (TROIDS).

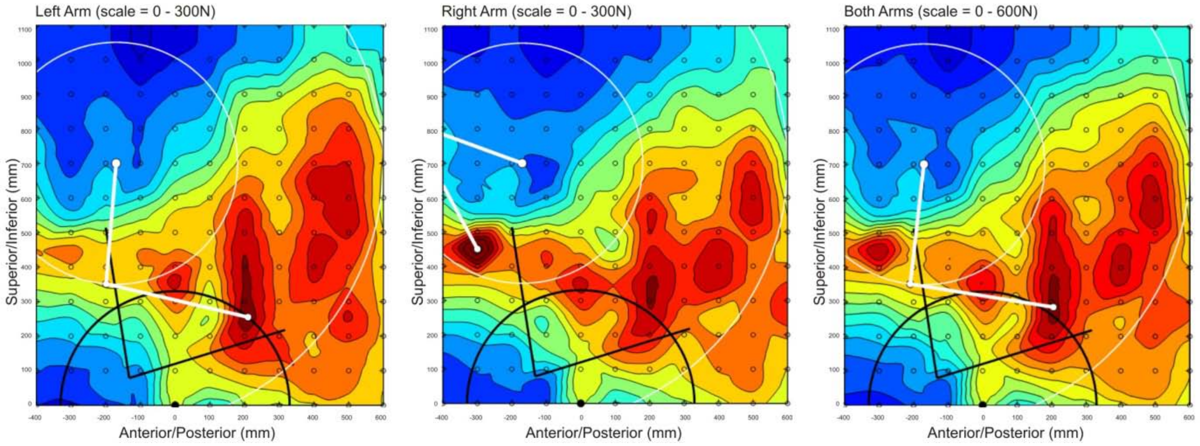

Figure 6. Force maps obtained for the subject with C7 tetraplegia.

The people in each group tested have particular motor and sensory function and this is illustrated in the distinctly different force maps. Given that the people with normal motor and sensory function have similar characteristics, Figure 3, it is likely that people in the three tetraplegic groups may be representative of other people with similar injuries.

4. IMPLICATIONS FOR DESIGN

This study shows that the ability to provide a force for tasks such as wheelchair propulsion will vary widely between subjects with different SCI's, between their arms and throughout the range of motion in the sagittal plane. As the aim of this study is to provide support for the design of effective assistive devices, such variations have to be understood and incorporated in the approach.

The research programme has thus concentrated upon the integration of three major issues. Firstly the modelling of a manikin in which such human variations can be represented, secondly to be able to incorporate realistic data, as has been illustrated in the previous sections, and finally to be able resolve and optimise the tasks.

All of this research has led to the construction of a constraint-based approach built upon the Bath Constraint Modeller which incorporated the ADAPS human model from the Technical University of Delft [11], [12], [13]. This uses rules to define the explicit tasks and requires the implicit rules necessary to create an articulated and life-like manikin. Within the manikin model are in excess of 22 body parts, related hierarchically or linked by greater than 52 degrees-of-freedom. All of these are themselves limited by defined boundary conditions. Such complexities has required the creation of new direct search approaches incorporating sensitivity analysis [14], [15], [16]. These research activities have led to a study of wheelchair sitting postures [17] that provide the basic models for humans interacting with a wheelchair.

The experimental studies, presented in this paper, are now to be incorporated into the manikin environment in order to allow the potential forces provided by the individual subjects to be assessed. The forces obtained from experimental measurements are read in and forces across the push rim of the wheel calculated. Within the constraint modelling environment design variables, such as positions and sizes of the wheels, can be selected and used in the optimisation of the design. With this approach the maximum stroke and forces can be obtained for individual cases.

As all wheelchairs are represented fully parametrically within the environment, various parameters can be changed and there effects observed. The position and size of the drive wheels have a considerable effect on both the social usability and balance of the chair, as well as changing the force profile that the user can provide. Furthermore, due to the difference in force mapping observed in the experimental studies, the modelling analysis predicts that different subjects will be able to achieve significantly improved force profiles, often with only subtle changes in chair geometry and sitting position. For people with tetraplegia, a small increase in capability may be enough to make the difference that allows an individual to use a manual wheelchair.

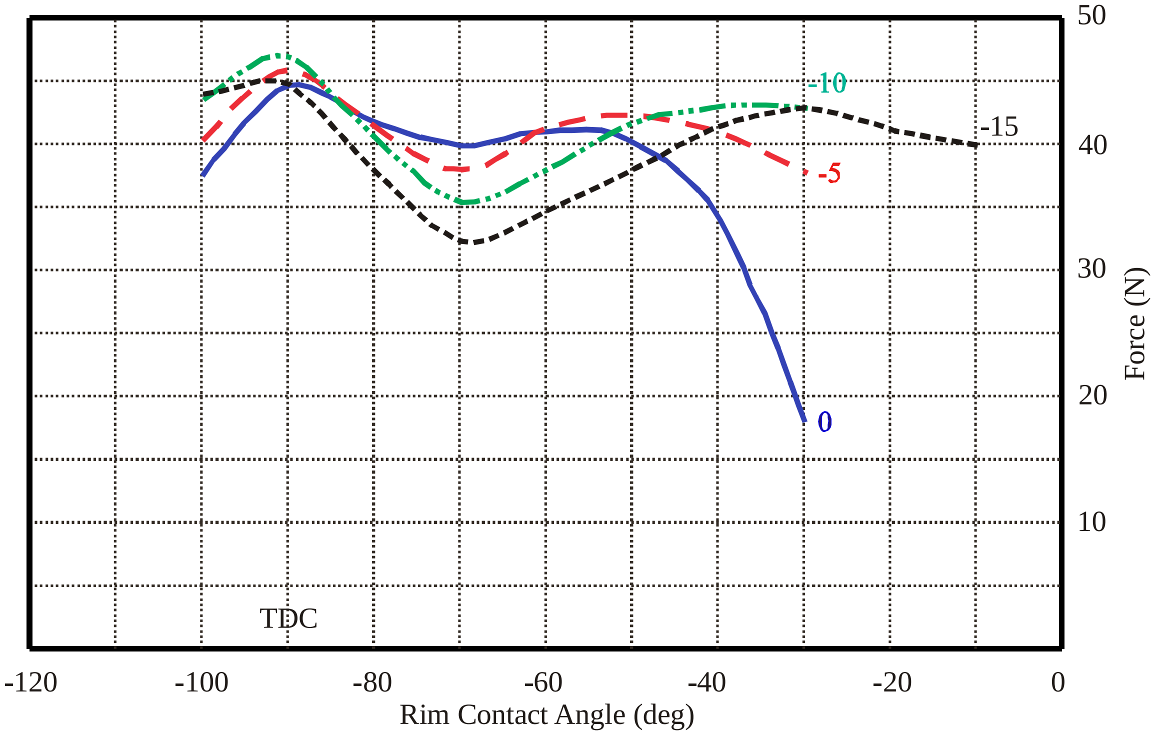

Figure 7. Showing the effect of lowering the seating position (in mm) for an individual.

In Figure 7, the effect of lowering the users sitting position on the force profile across the rim is easily seen. The effectiveness of this for the user is not only in the ability to gain higher forces throughout but selecting the regions in which greater forces can be provided. For example at –70 degrees the higher force is obtained at the original height but of pushing is required forward of –40 degrees then a lowering by -5 or –10 will provide a vastly improved capability.

5. STUDY OF PUSH RIM DESIGN

While it has been demonstrated that the model predicts an increase in propulsion ability for a small change in seat height, Figure 7, the force maps created from our experimental procedure indicate that a more marked improvements could be achieved with greater changes to push rim position. These potential improvements are, however, not within the limits of normal wheelchair adjustment. Consequently a number of design configurations are being investigated to allow such push rims to be practically achievable.

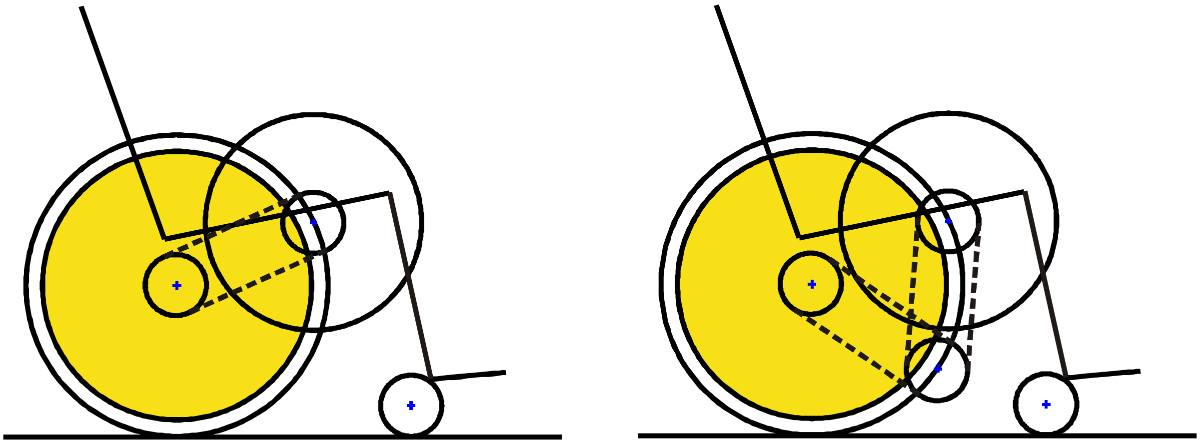

Figure 8. Showing principles to designs providing rim offset.

The simplest arrangement (shown in the first sketch in Figure 8) is to provide a chain drive between the driving wheels and a higher mounted push rim wheel. Such a solution could be implemented on an existing wheel chair but its position would need to be chosen to provide the improved forces required. This approach would result in the push rim being permanently fixed in position offset from the central wheel axis, which could be an inconvenience for other wheelchair activities.

For this reason a more advanced scheme is also to be investigated that provides both flexibility in push rim positioning and allows it to be lowered back to its original position at the drive wheel centre (where it can be used normally). This is shown in the second sketch and consists of a double chain (or gear) drive mounted on a v-linkage arrangement. The lower linkage mounted on the drive wheel centre can be locked in a forward mounted position, while the second linkage, mounted on the first is rotated to the preferred position for the rim wheel. Such a mechanism can be arranged to allow the rim wheel to be lowered down to align with the driving wheel centre. This design can thus be moved through a range of positions from the wheel centre position up to a higher force region selected by an investigation of the experimental data produced for a chosen individual.

In the study shown in Figure 9, the subject’s capability before and after the TROIDS surgery is compared with the predicted improvement possible through raising the push rim above the driving wheel. Whilst little is achieved beyond the –40 degree push position as the user starts to push from the –100 position nearly twice the force is obtained.

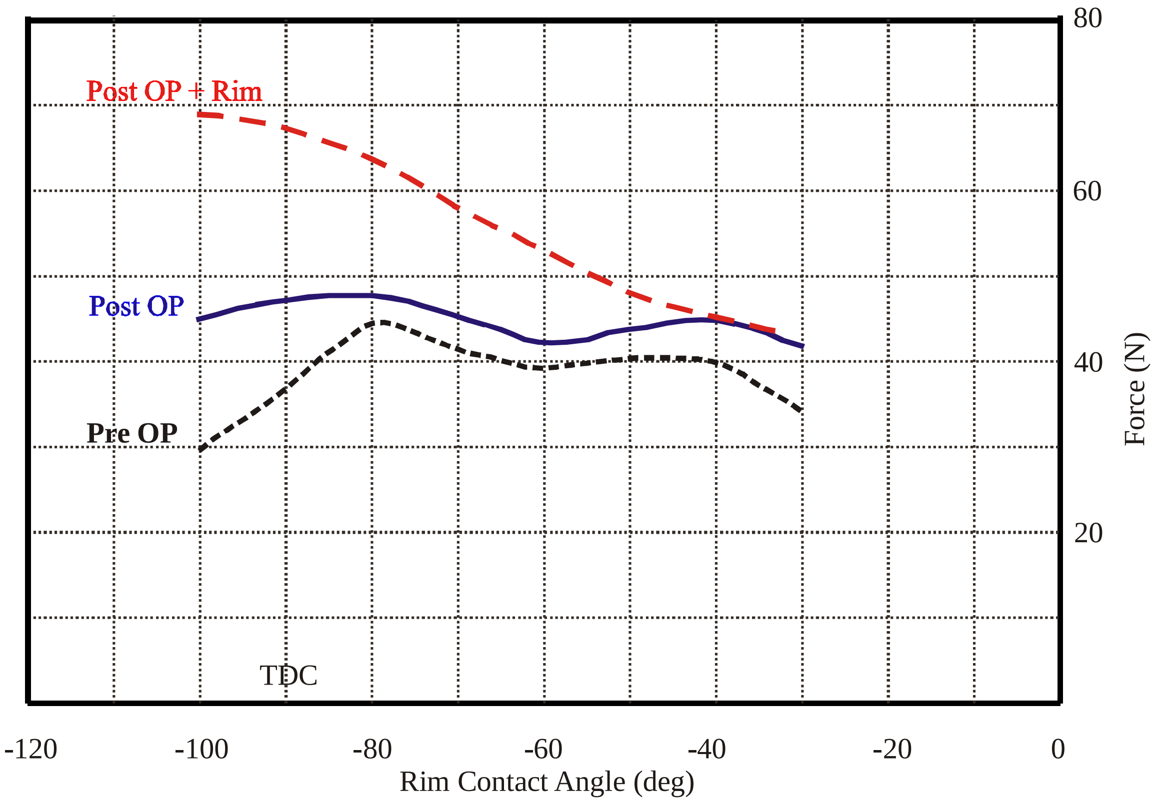

Figure 9. Force across push rim showing improvement due to rim offset.

6. CONCLUSIONS

This paper presents a novel method of characterizing human strength capability. It has been demonstrated that this method characterises the arm strength capability for able bodied subjects. Force maps have also been obtained for three subjects with tetraplegia. These three subjects had distinctly different motor and sensory upper limb control and where found to have distinctly different characteristic force maps. From the results of the able bodied participants it is likely that the tetraplegic subjects will be representative of people with similar injuries. Further work has commenced that involves measuring a large cohort of tetraplegic subjects in the three groups tested in this study, namely: those with no tricep function; those with TROIDS for arm extension; and people with C7 tetraplegia who have functioning triceps. The individual maps obtained will be a useful tool in establishing design parameters for the design of assistive devices in the future.

The constraint-based approach demonstrates the improvements in rim force that can be achieved with only subtle changes in wheelchair set up. From the force maps and the analysis using the Bath Constraint Modeller, it is likely that more marked improvements to wheelchair propulsion ability can be achieved by allowing the wheelchair user to apply the propulsion force closer to their area of maximum force. The design of a wheelchair with an offset push rim is now being evolved.

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