A Novel System for Wheelchair Stability Assessment

Design and Initial Results

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***Abstract*— Wheelchairs should provide safe and reliable functioning in various road conditions and situations, ease of propulsion, and high maneuverability. Often, wheelchairs need further modification and installation of additional equipment (ventilators, oxygen cylinders, etc) which affect their stability. Wheelchair stability is also dependent on a user's body characteristics that can result in a shifting of the centre of mass e.g. limb amputations, and obesity, etc. Adaptation of the wheelchair requires additional assessment and wheelchair tuning by highly skilled rehabilitation engineers. In this paper, we discuss the design and initial testing of a novel wheelchair stability assessment system. The developed WheelSense system consists of a force platform that senses the weight distribution of the wheelchair, the centre of the contact points, and the distances between contact points of the wheels. The measurement platform is linked via WiFi connection to a portable tablet computer where the platform's sensor signals are processed and the wheelchair stability parameters are calculated. An intuitive touchscreen GUI is used for visualization of the stability results and navigation through separate measurement modes. The mechanical platform was designed to be foldable and light-weighted and thus, to be easily transportable which gives additional advantages when the system is used outside of a clinical engineering department. The initial design is being evaluated through four prototype systems installed for clinical testing in 3 large hospitals in the UK. The initial results indicate that the developed measurement system possesses high accuracy and ease of operation.**

Keywords—wheelchair; wheelchair stability; static stability; centre of gravity; tipping angle; ISO 7176

I. INTRODUCTION

Wheelchair stability is a key issue for user safety. Loss of wheelchair stability can lead to a chair tipping and potentially injury to the user. Often, wheelchair stability becomes compromised by the installation of additional devices such as ventilators and oxygen cylinders, devices that help other user activity (rehabilitation robots), or heavy interface devices (wheelchair-mounted displays, communication aids, etc) [1, 2]. In other cases, the wheelchair's centre of gravity changes due to postural issues, limb amputations, or obesity [3]. Frequently, custom designed seating systems for posture correction and prevention of further posture deterioration need to be installed on the wheelchair. The systems for assessment of wheelchair stability become an important tool for measurement-based wheelchair reconfiguration and achieving optimal balance between stability and maneuverability.

ISO7176 are a series of standards used by wheelchair manufacturers to obtain and publish stability information about their wheelchairs. The static stability testing is covered by ISO7176-1 [4]. The same standard suggests placing the wheelchair on a standardized tilting platform and testing its stability at increasing angles of inclination [5]. ISO7176-2 is devoted to dynamic stability and tests the wheelchair when it is driven in the rearward, forward, and lateral directions [5]. In the tests suggested by ISO7176, a reference load is positioned on the wheelchair to simulate the occupant.

One of the most common stability testing approaches used in clinical practice within the National Health Service in the UK is based on a ramp that can be variably inclined. For the assessment (often called a "tilt test"), the wheelchair and occupant are positioned on the ramp that is gradually raised from horizontal. A simple pass-fail test verifies stability of the human-wheelchair system when inclined forwards, rearwards and sideways (12 degrees for manual wheelchairs and 16 degrees for powered wheelchairs) [6]. Tipping the wheelchair can often be an uncomfortable sensation for the user [1].

Software-based weighing and stability assessment systems have been introduced as an alternative to the standard tilt testing [7, 8]. These measurement systems have consisted of four weighing scales. The wheelchair and user are placed over the measurement plates and weight distribution across the four wheels when the wheelchair is inclined to preliminary known angles are measured. The weight distribution and wheelchair geometry measurements are used to calculate the position of the centre of mass and predict tipping angles by applying an algorithm associated with static equilibrium of the wheelchair system [9]. This approach reduces the manual handling and tipping risks associated with traditional stability testing. Whilst these systems are believed to improve patient experience and facilitate rehabilitation engineering practice, the system is large and heavy, hindering movement and transportation. Calculation requires 6 linear dimensions of the wheelchair to be manually measured and entered into the computer. An essential specific of the approach is that recorded weights correspond to sensor signals at the moment of measurement giving a "snapshot of the weight distribution" at the moment of measurement. Since sensor signals may fluctuate at the time of measurement due to electrical signal noises or unintentional movements of the patient, the calculation of the wheelchair stability may refer to sensor signal samples that do not represent the average value of the same signal but refer to some extreme values during signal fluctuation. Such sampled signals do not refer to the "history"of the signal changes and the approach is sensitive to electrical noise and random unintentional movement of the wheelchair occupier.

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In order to resolve the technical issues of previous designs, a new load cell based wheelchair stability assessment system (WheelSense) is being developed. The research on the technical aspects was supported by intensive analysis of user needs and solicited opinions from wheelchair prescribers, wheelchair users, manufacturers, and suppliers as well as analysis of the broader market [6].

II. RELATED WORK

The effects of different parameters of wheelchair configuration and user characteristics on wheelchair stability have been studied extensively from both theoretical and clinical perspectives including results of a study on the clinical application of a weight stability measurement system [7]. The study demonstrated that weighing systems can be used successfully as an alternative to the tilt testing approach. Research also comments on the clinical measurement of static rear stability [10]. In other studies, the effect of added loads, body position and wheelchair configuration on static rear and forward stability have been analyzed [11-14]. James [15] reports that an analysis of factors in manual wheelchair stability can be used to predict the effects on stability and manoeuvrability of adjustments to a manual wheelchair [15].

Wheelchair stability is important to the performance and safety of disabled athletes. Sport wheelchair stability has inspired work on the modelling and analysis of wheelchair stability in different sporting situations [16, 17]. Stability is an important issue not only for wheelchair design but also for automotive design. Studies on vehicle stability range from vehicle modelling, to automotive approaches for stability testing of cars, buses, tractors, etc. Some of these results can be applied easily to wheelchair design [18].

A number of research studies have been devoted to the development of active control technical systems that monitor wheelchair movement parameters and when necessary, automatically reduce wheelchair speed or prohibit further wheelchair movement in certain direction in order to preserve wheelchair stability [19]. Such systems apply special safety criteria for identification of situations that may lead to wheelchair instability. In some solutions, a matrix of preliminary calculated actions is used [20]. Other approaches for safe driving suggest analysis of the potential effect of intended user's commands on the wheelchair stability before their execution and reducing wheelchair speed for safe execution of the intended turning manoeuvre [21]. Modules for real-time stability analysis and prediction of the effect of intended commands can be integrated with the wheelchair controller.

III. METHODOLOGY

The methodology by which stability is calculated by the WheelSense system is described below.

A. System Structure

The block diagram of the wheelchair stability assessment system is shown in Fig. 1.

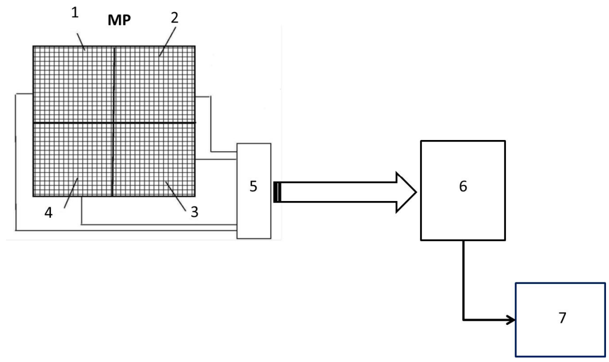

Fig. 1. A block diagram of the proposed system.

The wheelchair is positioned over the measurement platform (MP) that is comprised of four measurement plates (positions 1-4). Each plate has an array of load sensors. The sensors are of sufficient resolution to sense the load imposed by each wheel of the wheelchair and to detect the position of the center of pressure of that individual wheel. The distance between each pair of wheels is calculated from the positions detected by the sensors. The load cell signals of the separate plates are pre-processed by a pre-processing unit (position 5) and sent via Wi-Fi link to the tablet computer with signal processing and visualization software (position 6). The tablet has an output to a printer (position 7). In the tablet, sensor signals are analyzed. The forces applied to each plate and the distance between contact points are calculated. This allows the calculation of the position of the center of gravity and theoretical tipping angles. The same software gives a graphic illustration of the measured wheelchair stability parameters.

In contrast to existing systems that measure force parameters only once, the sensors in each plate of the developed system are monitored continuously during the assessment process. In this way, the system gives dynamic output which allows the effects to be shown of when the wheelchair is moved, or items are added. Sometimes, the wheelchair may not be positioned correctly, for example, in the case when one or more wheels do not make a proper contact with platform surfaces or when the wheelchair is moving slightly on the platform. Since sensor signals of all measurement plates are read continuously and current sensor signal flow is shown on the screen, eventual "unusual" signals or absence of weight signal from a plate can be noticed easily by the assessor and the wheelchair will be set in a correct position before actual measurement for stability calculation. For example, the Tuning toolkit mode of the stability software allows the assessor to see the real-time reaction force values for each wheel prior the measurement. If measured force from a plate shows 0 kg that alarms the assessor that the same wheel is not in contact with the scale's surface. The assessor can correct wheelchair position by moving it until all wheels are positioned inside the sensitive areas of the measurement plates for avoiding wrong results. A further significant advantage of the discussed design approach is that the platform can be designed to sense the wheels, and determine some dimensional information. This reduces the number of linear measurements that the user has to take and significantly simplifies the measurement procedure.

B. Measurement procedure

The WheelSense wheelchair measurement concept is explained in Fig. 2.

a/ b/ c/

Fig. 2. WheelSense measurement concept

During the measurement procedure, the wheelchair is moved sequentially and sensor data is collected in three positions. As shown in Figure 2, the procedure takes measurements on each of the following three steps:

Step 1: As indicated in Figure 2a, the front caster wheels rest on the plates 3 and 4 (see Fig. 1)

Step 2: The wheelchair is pushed forward until each wheel is on the platform, as shown in Fig. 2b.

Step 3: The caster wheels are rotated 180 degrees .

The data processing system calculates the various distances between wheels, as well as measuring the loads.

IV. DESIGN

A. Design approach

The design concept for the stability platform was to have a system that would "present itself", eliminating detailed instructions and training. The system would minimise the risks associated with stability testing and the associated manual handling issues for the wheelchair prescriber.

For portability, the platform was designed as four quadrants linked mechanically with suitable hinges. This allows ease of folding, while keeping electronic connections together (see Fig. 3).

B. Software

The software development for system functioning and the graphical user interface (GUI) were based on several requirements:

- The software scans continuously all sensors which allows easy detection of eventual wheelchair positioning errors, and prevents loss of information in communication errors.
- The GUI offers different levels of functionality appropriate for different levels of user.
- The GUI should be intuitive rather than requiring training and familiarization.

The GUI of the developed prototype system runs in an HTML 5 web browser (eg Chrome). A windows 8 tablet is currently being used for testing purposes.

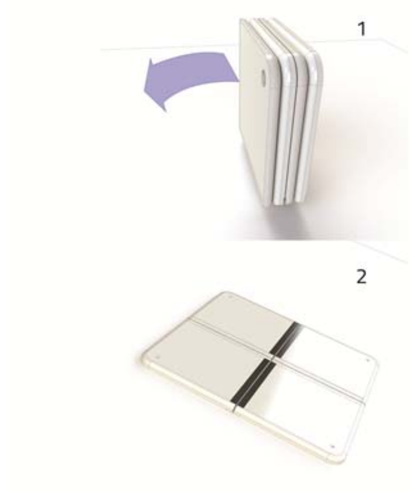

Fig. 3. The folding platform

C. Prototype design

The platform contains four force-sensitive plates. It is designed as a foldable aluminium frame. Planar beam load cells were used for the prototype design. Such load cells allow a compact design, possess good linearity, have stable characteristics and low noise. Sensor signals of the load cells are filtered and digitised. RS485 is used as a communication protocol for the sensor processing channels. A wireless portable router is used for transferring sensor signals to a portable tablet that uses Windows 8.1. The design allows the user to move freely around the platform and tested wheelchair while measuring wheelchair parameters. The operator can control the measurement dialogue via touch screen.

Fig. 4. The WheelSense measurement platform

A picture of the WheelSense prototype measurement system is shown in Fig. 4

The GUI is designed to be intuitive and simple to use. The user follows a series of prompts to make their way through the assessment process. A screen shot of the GUI is shown in Figure 5.

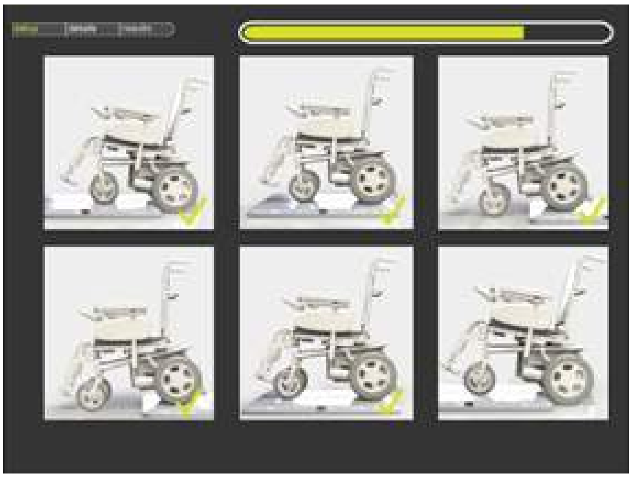

Fig. 5. A screenshot of the GUI

V. INITIAL TESTING AND RESULTS

The project has been guided by a user-centred design approach [6] with ongoing involvement of wheelchair prescribers and stakeholders guiding the design and development process. Currently, the system is under evaluation within NHS Trusts in the UK.

Following training, a range of practitioners including Wheelchair Prescribers, Rehabilitation Engineers and Occupational Therapists are using the new system over a 3 month period. Feedback on the usability of the system and the usefulness to clinical practise is being collected. The prescription experiences offered to wheelchair users is also being considered. Initial feedback suggests that the system has been well received and has the potential to guide tuning of wheelchairs in clinical practise.

VI. CONCLUSION

In this paper, we introduce a new system for wheelchair stability measurement. The system builds upon existing load cell measurement systems for stability testing. In the future consideration will be made of how the approach can be adapted to measure wheelchairs with 3, or 6 wheels.

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REFERENCES

[1] MHRA Device Bulleting DB2004 (02). Risk management. March 2004

[2] BHTA (2006). How stable is your wheelchair? Available at: http://www.pmguk.co.uk/publications/newsletters/Newsletter%20Vol%2022.pdf

[3] B. Sapey, J. Stewart, and G. Donaldson, “Increases in wheelchair use and perceptions of disablement”, Disability & Society, 20:5, 2005, pp. 489-505.

[4] International Standards Organization 1999, Wheelchairs— Part 1: Determination of static stability. ISO 7176-1: 1999 (E).

[5] International Standards Organization 1999, Wheelchairs— Part 2: Determination of dynamic stability. ISO 7176-2: 1999 (E).

[6] L. Moody, C.Chichi, S. Fielden, M.Heelis, D. Stefanov. Improving wheelchair prescription: an analysis of user needs and existing tools. Work: A Journal of Prevention, Assessment and Rehabilitation Volume 41, Supplement 1/ 2012 pp 1980-1984

[7] S. J. Caldicott and N. Sapcott, "Validation of a software-based stability assessment system for wheelchairs and their occupants", Journal of Medical Engineering & Technology, 2008, pp. 1-8

[8] P. Richardson, P. Dryer, T. Stevens, and J. Currell, “Wheelchair stability assessment-the budget route”, Recent Advances in Assistive Technology and Engineering (RAATE), Birmingham, 2004, Conference Proceedings, pp. 8–9.

[9] A Wawrzinek and U Boenick, “Dynamische stabilität von rollstühlen”, Biomed Technik 3 2 , 1987, pp. 313-343.

[10] R. Lee Kirby, “Clinical Measurement of the Static Rear Stability of Occupied Wheelchairs”. Arch Phys Med Rehabil , 1999, pp. 199-205.

[11] R. Lee Kirby, “Adding Loads to Occupied Wheelchairs: Effect on Static Rear and Forward Stability”, Arch Phys Med Rehabil , 1996, pp. 183-186.

[12] R. Lee Kirby, “Wheelchair stability: Effect of body position.”, Journal of Rehabilitation Research and Development Vol 32 No. 4 , 1995, pp. 367-372.

[13] R E. Cowan, “Impact of Surface Type, Wheelchair Weight. and Axle Position on Wheelchair Propulsion by Novice Older Adults.” Arch Phys Med Rehabil , 2009, pp.1076-1083.

[14] G. Trudel, “Effects of Rear-Wheel Camber on Wheelchair Stability”, Arch Phys Med Rehabil , 1997, pp. 78-81.

[15] J D Tomlinson, “Managing Maneuverability and Rear Stability ofAdjustable Manual Wheelchairs: An Update”, Phys therapy, 2000, pp. 904-911.

[16] R A Cooper, “Racing wheelchair roll stability while turning: A simple model. Journal of Rehabilitation Research and Development “, 1992, pp. 23-30.

[17] P-L Bernard, “Balance and stabilization capability of paraplegic wheelchair athletes”, Journal of Rehabilitation Research and Development Vol. 31 No. 4 , 1994, pp. 287-296.

[18] A. Fabbri and al, “Static Measurement of the Centre of Gravity Height on Narrow-track Agricultural Tractors”, Biosystems Engineering , 2004. 299-304.

[19] G. Boiadzjiev and D. Stefanov, “Powered Wheelchair Control Based on the Dynamical Criteria of Stability”, International Journal of Mechatronics, Elsevier, Vol. 12, No 4, 2002, pp. 543-562

[20] G. Boyadjiev, D. Stefanov, “Condition for Retaining Equilibrium During the Motion of a Wheelchair”, Journal of Theoretical and Applied Mechanics, Vol. 3, 1991, pp. 15-20

[21] D. Stefanov, “Powered Wheelchair Controller with Dynamic Stability Checking”, Rehabilitation R&D Progress Reports 1992 - 1993, Department of Veterans Affairs, Baltimore, pp. 410-411