An Approach to Measure Wheelchair Stability. Concept and Benefits

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Abstract— **Wheelchair stability is dependent on user's body characteristics that can shift significantly the original center of mass in the cases of limb amputation, severe skeletal deformities or obesity. The center of gravity may change with the installation of additional devices such as oxygen cylinders or ventilators on the wheelchair. Therefore, quantitative evaluation and prediction of the behavior of the user-wheelchair system in a variety of static and dynamic situations is essential for user's safety and for the optimal tuning of the human-wheelchair system.**

In this paper we discuss an approach for wheelchair stability assessment that only requires two inclinations and weight measurements. We also discuss the algorithm associated to the procedure based on the use of the reaction forces in the contact points of the wheels measured by the load cells. Further, the paper includes an analysis of the influence of the errors in measurement of the input parameters on the output results and demonstrates that the proposed approach possesses high accuracy.

The advantage of the proposed approach is the use of a reliable procedure based on three simple steps and five weight measurements with four independent load scales which may lead to the design of an affordable and accurate measurement system.

I. Introduction

Wheelchair stability is a key issue for the safety of wheelchair users. In many cases, wheelchair incidents could be prevented by assessment of the stability of human-wheelchair system and further adjustment of the wheelchair. Often, original wheelchair design is modified with the installation of additional essential devices such as oxygen cylinders or ventilators required by numerous users. This affects wheelchair performances and standard wheelchair capabilities. If the shifting of the center of gravity is known, the same additional devices can be positioned on much optimal way to cause minimal change of stability characteristics. In other cases, stability may be compromised by body characteristics, such as severe body deformities and extraordinary postures, limb amputations or obesity. On the other hand, an increase in stability typically results in a decrease of maneuverability and steering characteristics. Wheelchair tuning therefore consists in reaching a compromise between stability and maneuverability. Optimal wheelchair adjustments can be achieved by reference to the stability measurements of the human-wheelchair system.

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The International Standard Organization has regulated the assessment of both static and dynamic stability of wheelchairs with the standards series ISO 7176. The latest revision of sub-standard ISO7176-1 [1] released in 1999 suggests the assessment of wheelchair stability by using a standardized tilting platform. The test assesses the stability of the wheelchair when inclined forward, rearwards and sideways. A dummy is used to simulate the occupant during the test to remove evident risks to the users during the procedure [1]. On the other hand, the ISO 7176-2 [2] standard requires the assessment of the dynamic behavior of the wheelchair according several tests scenarios, where the wheelchair is driven forward, rearward and sideways and the ability of the wheelchair to remain stable in several extreme situations is observed. Often, in clinical practice in the UK, wheelchair stability is assessed with a pass or fail test (called "tilt test"), where the wheelchair with the user on it is inclined on angle of 12 degrees (for manual wheelchairs) and on 16 degrees for electric wheelchairs.

Tilt tests are often stressful for wheelchair users as their procedure is based on tilting the wheelchair in its least stable condition. Such tests usually take long time and need to be performed by highly qualified engineers. Software-based weighing and stability assessment systems have been introduced as an alternative to the standard tilt testing [3, 4]. These measurement systems have consisted of four weighing scales. In this paper, we introduce a new stability-assessing method based on sideways and backward tilts of the wheelchair and new simple algorithm for calculation of the wheelchair stability limits in all directions. The proposed approach is based on reduced number of load cells and small number of measurements. The paper also includes results from numerical testing and evaluation of the presented method. Results demonstrate the advantages of the new approach in comparison with other existing methods.

II. Methodology

A. Related Works

Numerical methods for stability assessment possess a number of important advantages in comparison to stability assessment methods based on physical verification of the stability of human-wheelchair system [5]. As a difference from physical methods for determination of the maximal stability angles that use visual observation of the moment when the physical system will lose its stability, these methods are based on calculations and require slight tilting of the wheelchair, usually by few degrees. Therefore, numerical methods for stability assessment improve user's

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experience and safety during the test and increase the accuracy of the results.

Usually, numerically-based stability assessment procedure begins with measuring the weight under the four wheels and the information is then used for the calculation of the coordinates of the centre of mass in the horizontal plane. Then, the wheelchair is usually tilted backwards, the new weight distribution in the contact points is measured and results are used to estimate the z-coordinate of the centre of mass. Calculation algorithm also requires several additional geometrical measurements of the distances between contact points and wheelchair geometry [6]. Results from a detailed study on the clinical application of a weight stability measurement system and their clinical perspectives are presented in [3]. In [4], Kamber proposes a low-cost portable system based on a servo-controlled tilt platform to model daily life activities. Numerous stability approaches have been driven by the needs of automotive industry for stability testing of cars, buses, tractors, etc. Some of these results can be applied easily to wheelchair design [7]. Special safety criteria to identify situations that may lead to wheelchair instability have been proposed in [8].

B. *Concept*

The procedure is using four independent load cells fixed on a rigid frame. The frame should have high stiffness to prevent any residual deformations during the procedure leading to errors on the results.

For the test, the wheelchair with the user sat on it is placed on the platform so that each of the wheelchair's wheels is positioned on a separate load cell, as shown in Fig. 1.

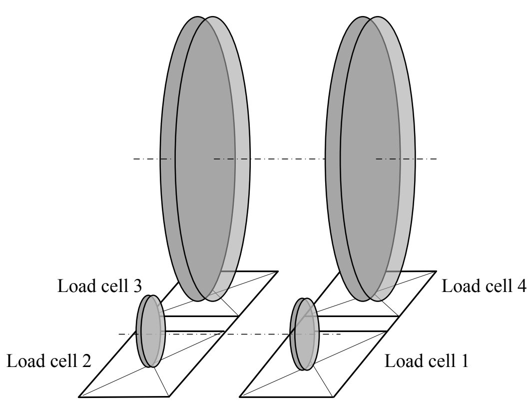

Figure 1. Wheelchair placed on independent load cells

During lateral inclination of the measurement platform, the front wheels may turn around their vertical axes that may entail a situation in which the wheelchair will tend to roll down the slope. In order to prevent the wheelchair from eventual rolling, brakes should be applied on the rear wheels and the movement of castor wheels around their vertical axes needs to be disallowed. The test procedure is based on recording five weight measurements under three inclinations of the measurement platform: horizontal, lateral incline and backward incline. The procedure consists of the following steps as illustrated on Fig.2:

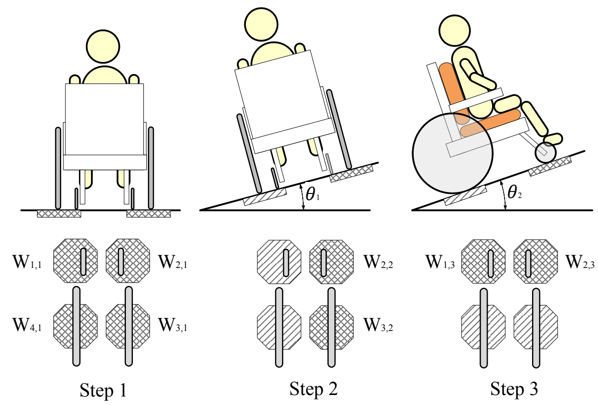

Figure 2. Steps of the procedure and weight measurements

- Step 1: The measurement platform remains horizontal and the weight under each of the four wheels is measured. During the calculation procedure, these results are used to calculate the weights under the right wheels, front wheels, as well as the total weight of the system.
- Step 2: The platform is inclined laterally towards the left by an angle θ_1 and the weight under both right wheels are measured.
- Step3: The measurement platform is inclined along the long wheelchair axis by an angle θ_2 and the weight under both front wheels is measured.

The stability assessment procedure merely requires five weight measurements and does not necessitate any geometrical measurements. The process of geometry measurements frequently is a lengthy manual process that may source additional errors on the final stability angles. The proposed algorithm easies measurement procedure, increases its efficiency, and does not require geometrical measurements.

The lateral and backward test inclination angles (θ_1 and θ_2 respectively) can be measured precisely by using an electronic inclinometer, for example. The accuracy of stability prediction results depends on the level of tilting of the platform. On practice, angles θ_1 and θ_2 can be selected to remain within the range of around 5 degrees which is a quite usual inclination when a wheelchair travels on the road and such tilt value does not cause stress to the user. As demonstrated below (see Fig. 3) such inclination values allow the calculation of stability angles with enough accuracy.

C. *Algorithm for Calculation of Maximum Inclination Angles*

The maximum leftward stability angle α_{max} defined as the ability of the wheelchair to remain stable while right wheels are lifted is obtained from the following equation:

$$90 - \tan(\alpha_{max}) = \left(\frac{W_{RiW(flat)}}{W_{RiW(inclined)}} - \cos(\theta_1)\right)\left(\frac{1}{\tan(\theta_1)}\right) \quad (1)$$

where,

$W_{RiW(flat)}$ Weight under both right wheels while flat (step 1). $W_{RiW(flat)}$= $W_{2,1}$+$W_{3,1}$ (as per Fig.1)

$W_{RiW(inclined)}$ Weight under both right wheels while inclined (step 2)

$W_{RiW(inclined)}$ = $W_{2,2}$+$W_{3,2}$ (as per Fig.1)

θ_1 Sideways test inclination angle (step 2).

The maximum rightward stability angle β_{max} defined as the ability of the wheelchair to remain stable while left wheels are lifted is obtained with the following equation:

$$\sin(\beta_{max}) = \left(\frac{W_{total(flat)}}{W_{total(flat)} - W_{RiW(flat)}} - 1\right)\sin(\alpha_{max}) \quad (2)$$

where,

$W_{total(flat)}$ Weight under four wheels while flat (step 1)

$W_{total(flat)}$ = $W_{1,1}$+$W_{2,1}$+$W_{3,1}$+$W_{4,1}$ (as per Fig.1)

$W_{RiW(flat)}$ Weight under both right wheels while flat (step 1)

$W_{RiW(flat)}$ = $W_{2,1}$+$W_{3,1}$ (as per Fig.1)

α_{max} Maximum leftward stability angle.

The maximum backward stability angle γ_{max} defined as the ability of the wheelchair to remain stable while front wheels are lifted is obtained with the following equation:

$$90 - \tan(\gamma_{max}) = \left(\frac{W_{FrW(flat)}}{W_{FrW(inclined)}} - \cos(\theta_2)\right)\left(\frac{1}{\tan(\theta_2)}\right) \quad (3)$$

where,

$W_{FrW(flat)}$ Weight under both front wheels while flat (step 1)

$W_{RiW(flat)}$= $W_{1,1}$+$W_{2,1}$ (as per Fig.1)

$W_{FrW(inclined)}$ Weight under both front wheels while flat (step 3)

$W_{RiW(flat)}$= $W_{1,3}$+$W_{2,3}$ (as per Fig.1)

θ_2 Backward test inclination angle (step 3)

The maximum forward stability angle δ_{max} defined as the ability of the wheelchair to remain stable while rear wheels are lifted is obtained with the following equation:

$$\sin(\delta_{max}) = \left(\frac{W_{total(flat)}}{W_{total(flat)} - W_{FrW(flat)}} - 1\right)\sin(\gamma_{max}) \quad (4)$$

where,

$W_{total(flat)}$ Weight under four wheels while flat (step 1)

$W_{total(flat)}$ = $W_{1,1}$+$W_{2,1}$+$W_{3,1}$+$W_{4,1}$ (as per Fig.1)

$W_{FrW(flat)}$ Weight under both front wheels while flat (step 1)

$W_{RiW(flat)}$= $W_{1,1}$+$W_{3,1}$ (as per Fig.1)

γ_{max} Maximum backward stability angle.

The algorithm presented above mainly contains fractions between measured weights that were presented in their most simple form although these modifications were made with regards the simplicity of the procedure and design of the testing platform. These fractions also add to a high degree of robustness of the algorithm as it will be less dependent on external sources of errors such as temperature changes.

The integrity of the model was verified for extreme load cases by verifying the result of the equations for weights tending to 0. It was shown that while $W_{RiW(inclined)}$ and $W_{FrW(inclined)}$ tend to 0, the associated leftward or backward stability angles tends to the value of the test inclination angle α. Variations of the test inclination angles θ_1 and θ_2 result in a variation of the weight ratios of the equations presented above. In other words, several combinations of test inclination angles and weight ratios may be found for a similar stability angle. This demonstrates the suitability of the suggested equations if the maximum tipping angles remain above the test inclination angle α and therefore contact of the four wheels of the wheelchair is kept during the entire procedure.

D. Practical Implementation

A numerical assessment of the accuracy of the results provided by the above-described stability test procedure was carried out. Values of weight and inclination angles likely to occur during the procedure were input into the equations presented above and the results provided were analyzed. A numerical approach was adopted to simplify the study and narrow the input of this analysis to the most likely encountered weights and test angle.

The analysis has demonstrated that the accuracy of all four stability angles is mostly influenced by the accuracy of the inclination angle α.

The numerical analysis was performed with α = 4.0 degrees which guarantees that highly unstable wheelchairs (for example, sport wheelchairs) will remain stable during the test to provide accurate results as per Fig. 2.

Fig.3. presents the generic impact of the test angle α on the final stability angles when α is varying from 0.5 to 7.5 degrees. This shows the higher the angle α, the lower the impact of its inaccuracy on the final tipping angles.

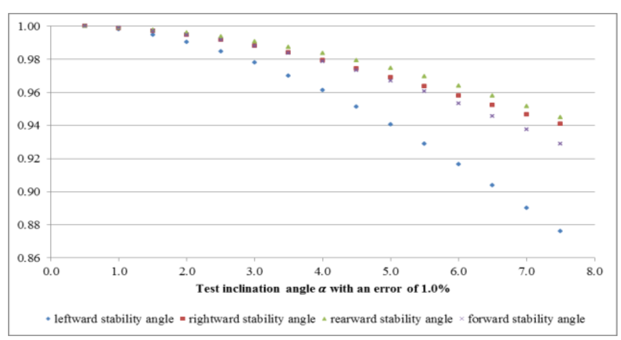

Figure 3. Inclination angle α against dimensionless impact on final stability angles

Errors on final tipping angles increase while the angle α increases. This tends to reveal that no optimal angle α that would provide the smallest error can be found for this method. However, the impact of a small error will tend to decrease with a larger angle α to a larger degree for leftward stability angle than backward stability angle.

Contrary to previously proposed methods [6], this procedure suggests the tilt of the four load cells in order to maintain a high level of accuracy on the angle α. The angle is therefore independent from the distance between the pair of wheels that is being lifted and the opposite pair. The angle α will be determined during the design of the stability assessment platform comprising a rigid frame and four load cells therefore allowing high precision on its measurement.

The analysis also revealed that errors on weight measurements remain the same for all weight measurements and do not have any influence on the final stability angles. This is due to the fact that the original algorithm uses ratios of weights measurements therefore cancelling any errors made both on the dividend and the divisor. Therefore, the accuracy of the load cells may be, to some extent, reduced to limit the cost of the hardware require for the stability assessment procedure without influencing the result of the analysis.

The angle α requires particular attention as it represents the most critical parameter of the system. It was found that an error of +1% on α may underestimate forward stability angle by 0.2%, backward stability angle by 0.6%, rightward stability angle by 1.5% and the leftward stability angle by 1.0%. The test inclination angle has a bigger impact on rightward stability. It is also worth noticing that the determination of this angle does not depend on the geometry of the wheelchair. However, measurement accuracy may be influenced by mechanical factors such as the deformation of the platform frame or the deformation of the wheelchair tires.

It was also found that a uniform distribution of negative and positive errors on weight measurements equally overestimates and underestimates the final stability angles. Hence, a negative error on $W_{RiW(flat)}$, $W_{FrW(flat)}$, $W_{total(flat)}$ tends to underestimate the final tipping angles while a positive error on these parameters tends to overestimate the final tipping angles. On the other hand, a positive error on α, $W_{RiW(inclined)}$, $W_{FrW(inclined)}$ tends to underestimate the final tipping angles while a negative error on these parameters tends to overestimate the final tipping angles.

For clarity of introduction of the approach, above we referred to 4 load plates. However, the test may be performed with fewer load cells as well, for example, by using a long-sized plate for measurement of the weight under both front wheels of the wheelchair at once and rotating the wheelchair in order to weigh the force caused by both left wheels with the same long-sized load plate. Although this will result in additional steps, it will provide further simplification of the measurement platform.

Further investigations should be carried out on the accuracy of loads cells while the test platform is inclined. The horizontal component induced while the system is tilted is compensated by the friction of the tire on the load cell. It is therefore essential to design a grip on the surface of the load cells to prevent any sliding of the wheelchair during the procedure.

III. CONCLUSION

In this research, we introduce an alternative method for the assessment of the static stability of wheelchairs defined by four stability angles. Compared to conventional methods, the main advantage of the method resides in its simplicity and decreased number of parameters required by the associated algorithm.

The analysis considers a static situation of the system therefore excluding body movements and vibrations, commonly source of measurement errors. The weights measured with the load cells may be post-processed to cancel the noise due to external sources of errors.

Despite presenting a procedure with an additional step, this method entirely use the experimental aspect of the concept. Indeed, the proposed algorithm does not need any modification to account for the different geometries of wheelchairs currently available on the market. Besides, although initially developed for 4-wheel wheelchairs, this method may be adapted to wheelchairs equipped with 3 wheels without any modifications. The procedure may also assess the stability of 6-wheel wheelchair with minimal adaptation of the forward and backward stability assessment procedure consisting in installing the middle and front wheels on the same pair of load cells before the tilt. The algorithm will simplify the system by considering both middle and front wheels as a unique pair of wheels.

Further investigations are required to design a reliable stability test platform to accommodate the load cells and provide quick and trustworthy results. It is certain that the stiffness of the components used as well as the portability of the whole system will remain key factors in the design process.

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