Quantification of the user-wheelchair system stability based on the CoP trajectory within the base of support

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 72 (2014) 368 – 373

Procedia Engineering

www.elsevier.com/locate/procedia

The 2014 conference of the International Sports Engineering Association

Quantification of the user-wheelchair system stability based on the CoP trajectory within the base of support

Matteo Cognolato[a], Nicola Petrone[a]*, Giuseppe Marcolin[a]

[a]*Department of Industrial Engineering, University of Padova, Via Venezia 1 35131, Padova, Italy*

Abstract

Aim of the work was the introduction of a user-wheelchair Stability Index able to give objective information to find the most appropriate wheelchair settings both for daily and sports use. The Stability Index was introduced after asking two users to assume four pre-defined postures over a dynamometric force platform and measuring the centre of pressure (CoP) trajectory. After identifying the base of support centroid Ctd and the instantaneous CoP, the Stability Index expresses how far is the instantaneous CoP from the sides of the base of support outline: the index is calculated with respect to each direction (forward, rearward, right and left side) and referred to the centroid of the base of support. The Stability Index values increase proportionally with the stability: a zero value means that CoP is on the outline, a unit value corresponds to coincidence between CoP and Ctd. A preliminary evaluation of the Stability Index was performed by varying both back adjustment and user posture. The proposed method only requires a force plate or a stabilometric plate. The evaluation of user-wheelchair system stability can be performed in real time, merging this objective parameter with user subjective feeling in order to propose the most satisfactory solution to users, manufacturers and clinicians.

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University

Keywords: wheelchair, Stability Index, posture, safety.

* Petrone Nicola. Tel.:+39 049 8276761.
E-mail address: nicola.petrone@unipd.it

Selection and peer-review under responsibility of the Centre for Sports Engineering Research, Sheffield Hallam University
doi:10.1016/j.proeng.2014.06.102

1. Introduction

Wheelchairs allow disabled persons to recovery their social inclusion and are essential assistive products suitable to young and old people willing to have an independent locomotion despite their disability.

The stability of the user-wheelchair system is a fundamental safety requirement from a user's point of view. Theoretically, a user-wheelchair system is statically stable as long as the gravity force line from the centre of mass of the user-wheelchair system is inside the base of support, that is the area on the ground confined by the outline of the contact points of its wheels (ISO 7176-1). In the present ISO standards, the stability of a wheelchair is evaluated after placing a standard dummy on the wheelchair (ISO 7176-11) and evaluating the minimum tipping angle at which any wheel looses contact from the ground in the forward, rearward and lateral directions. Since the location of the centre of mass is in general not known, the tipping angle is determined after placing the wheelchair on a test platform the slope of which can be adjusted. The angle of the slope on which the wheelchair starts to tip is measured. The slope angle of the test platform represents the tipping angle in that direction (ISO 7176-1).

It has to be clear that a wheelchair presenting a small tipping angle, for instance in the rearward direction, is not always a bad wheelchair: in fact, for active users with full ability of upper limbs, being able to lift easily the front castor wheels to overcome a step is again a functional requirement.

The stability property of a user on its wheelchair is usually evaluated empirically by the user and the clinicians in order to choose the best wheelchair or its best adjustment. User's feeling and technicians experience are frequently the criteria used for stability evaluation: this can be seen as a *subjective evaluation approach*. With regard to the usability and safety of assistive products, there is a need of an *objective evaluation approach* to quantify the stability level of the real system constituted by the user and the wheelchair. A quantification of user-wheelchair stability might be used together with the subjective criteria in order to develop an approach that might integrate both subjective and objective information. Thanks to the *integrated approach*, different wheelchair models and settings could be compared, providing useful information to both users and manufacturers for a more aware development and use of the device.

It is a common experience that the tipping of a solid object laying over an inclined surface can occur when the gravity force line (Center of Gravity) of the user-wheelchair system is not more falling inside the base of support, defined as the outline of the polygon individuated by the wheels contact points. On the other hand, the user-wheelchair system Centre of Pressure *CoP* (the point of application of the Ground Reaction Force) contains the system stability information and its instantaneous position could predict a fall, in analogy to the analysis of stability in standing posture (Winter (2009)).

In order to quantify the stability and to proceed towards an *integrated approach*, an index based on the *CoP* trajectory has been defined in the present work. In addition, a preliminary evaluation of this Stability Index has been carried out after changing two of the fundamental parameters for user-wheelchair stability: the wheelchair back support adjustment and, as early reported in Kirby et al. (1995), the user posture.

Nomenclature

SI_F	Forward Stability Index
SI_B	Rearward Stability Index
SI_R	Right Stability Index
SI_L	Left Stability Index
SSI	Static Stability Index
α_{BS}	Back support to seat angle
CoP	Centre of Pressure
Ctd	Base of support centroid
FA	The most forward adjustment of the back support
IA	The intermediate adjustment of the back support
BA	The most rearward adjustment of the back support

2. Materials

A rigid manual wheelchair, model Zodiac produced by Offcar (IT), was used in combination with a Bertec force platform (60x40 cm at 960 Hz sample rate) and a BTS Optoelectronic system (6 cameras at 60 Hz sample rate). A wooden surface of 20 mm thickness was fixed on the top of the force plate (without any other ground contact points) to increase the support surface and enable also wide wheelchairs to undergo the test.

The Stability Index can be evaluated using a single force plate. In this preliminary evaluation the optoelectronic system was used to implement the calculation of the Stability Index using BTS embedded software and to have a quick and simple data validation.

3. Method

3.1. Stability Index definition

The base of support is defined by the wheel-ground contact points (Fig. 1a,b), that can vary in general depending on the wheelchair trajectory prior of the stop. In this study, in order to obtain a trapezium as base of support, the front castor wheels positions were fixed.

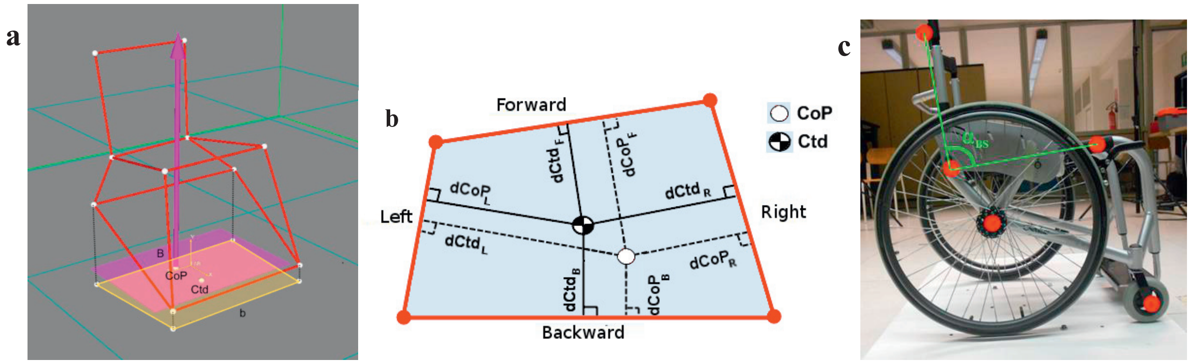

Fig. 1 . (a) Wheelchair model from the optoelectronic motion capture with the highlighted base of support; (b) Top view of a general base of support; (c) Markers position and α_{BS} angle

The Centroid of the Base of Support *Ctd* has been defined as the centroid of the polygon corresponding to the base of support, depending of wheelchair geometry and front castor wheels orientation. In this study the *Ctd* was calculated as the centroid of a regular trapezoid. In real use, front wheels are not fixed and the ground contact polygon shape is changing during turns and, consequentially, the *Ctd* calculation (Fig. 1b).

The Stability Index has been defined as a four elements vector containing instant values calculated for each direction (forward, backward, right and left side):

$$StabilityIndex(t) = \begin{bmatrix} SI_F & SI_B & SI_R & SI_L \end{bmatrix} = \begin{bmatrix} \dfrac{dCoP_F}{dCtd_F} & \dfrac{dCoP_B}{dCtd_B} & \dfrac{dCoP_R}{dCtd_R} & \dfrac{dCoP_L}{dCtd_L} \end{bmatrix} \quad (1)$$

where

- *dCoP* is the instantaneous *CoP* distance from each base of support polygon side (Fig.1b)
- *dCtd* is the instantaneous *Ctd* distance from base of support polygon side (Fig.1b)

The *dCtd* values depend on the wheelchair geometry and front wheels position, the *dCoP* depends both on the user anthropometry and posture (Fig. 1b).

The Stability Index can get values between 0 and 2. The index gets a 0 value when the distance between *CoP* and the side is null and this situation represents incipient user-wheelchair system instability. Ideally, high stability occurs when the *CoP* and *Ctd* position are coincident and this condition gives a Stability Index equal to 1. A value larger of 1 of the Stability Index indicates an excess of stability in that direction that, however, corresponds to a decrease in the other component of Stability Index referring to the opposite side.

The Stability Index could be summarized with its minimum value which gives a time dependent scalar indicator of the value (and direction) of the lowest user-wheelchair system stability.

After observing that, ideally, there is a seated position that represents the ideal correct sitting posture of the user (pelvis contacting the seat and the back support, trunk contacting the back support, foot on the foot support, hands midway on the handrail), this was taken as a reference position to evaluate the user-wheelchair system Static Stability Index (SSI). The minimum value of the Stability Index with the user in the reference position resulted to be typically in the rearward direction (Fig. 3a): the SSI was then expressing this value.

3.2. Stability Index preliminary evaluation

The Stability Index evaluation was performed changing only one variable at time: the subject and the back support adjustment, despite the fact that the wheelchair used in this study presented several other available adjustments (seat, front wheels and footrest position). A marker was placed on each wheel axle and the wheel ground contact point was given by its projection on the horizontal plane: moreover, in order to obtain the angle α_{BS} between the back support and the seat, others two markers where placed on back support and seat (Fig. 1c).

User-wheelchair system stability is strongly influenced by the user posture as reported in Kirby et al. (1995): therefore to perform a preliminary evaluation of the Stability Index five positions were individuated:

- Seated reference position: subject trunk upright with hand midway on handrail (Fig. 2a);
- Forward position: subject leaning forward with straight arms (Fig. 2b);
- Rearward position: subject leaning backwards with hand behind head (Fig. 2c);
- Right position: subject leaning to the right with straight arms (Fig. 2d);
- Left position: subject leaning to the left with straight arms (Fig. 2f).

Each of these postures was assumed in a quasi-static sequence by two able bodied volunteers (Male and Female) with three different back support positions: the most rearward back support adjustment, the intermediate adjustment and the most forward adjustment.

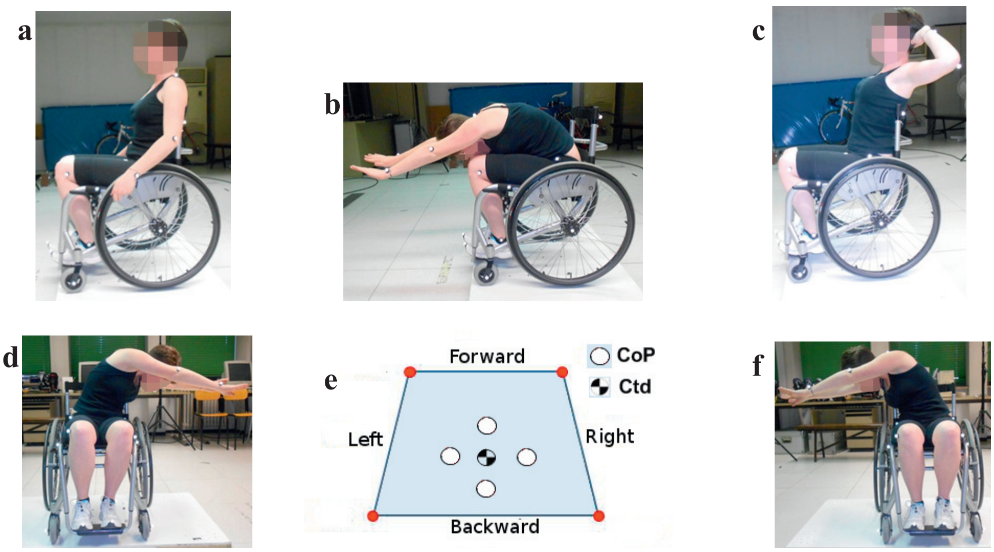

Fig. 2. (a) Seated reference position; (b) Forward position; (c) Rearward position; (d) Left position; (e) Example of CoP positions with different postures (f) Right position

4. Results

Tables 1 and 2 report the minimum Stability Index value for the forward, rearward and lateral posture in function of back support position.

Table 1. Minimum Stability Index during movements: male subj

Adjustment	α_{BS}[°]	SSI	SI_F	SI_B	SI_R	SI_L
FA	78.4	0.506	0.350	0.261	0.697	0.596
IA	86.5	0.311	0.210	**0.026**	0.541	0.401
BA	93.2	0.227	0.420	**0.006**	0.584	0.523

Table 2. Minimum Stability Index during movements: female subj.

Adjustment	α_{BS}[°]	SSI	SI_F	SI_B	SI_R	SI_L
FA	77.5	0.581	0.576	0.171	0.402	0.652
IA	86.0	0.377	0.653	**0.075**	0.643	0.578
BA	92.7	0.296	0.515	**0.010**	0.595	0.665

Two examples of Stability Index instantaneous values during quasi-static movements of the subject when transitioning between the different postures are presented in Fig. 3.a and 3.b. The corresponding *CoP* trajectory referred respectively to the FA Test (Fig. 3a) and BA Test (Fig. 3b) are presented respectively in Fig 3c and 3d.

The back support adjustment has a large influence in user-wheelchair system stability: The forward and rearward Stability Index components calculated during BA Test (Fig. 3b) shows the same trend but greater modulus than the FA Test (Fig. 3a). This consideration is well highlighted observing the *CoP* trajectory: in the BA Test (Fig. 3d) the *CoP* is constantly closer to the rear outline than in the FA Test (Fig. 3c) but this have not a big influence in the *CoP* motions on the others directions.

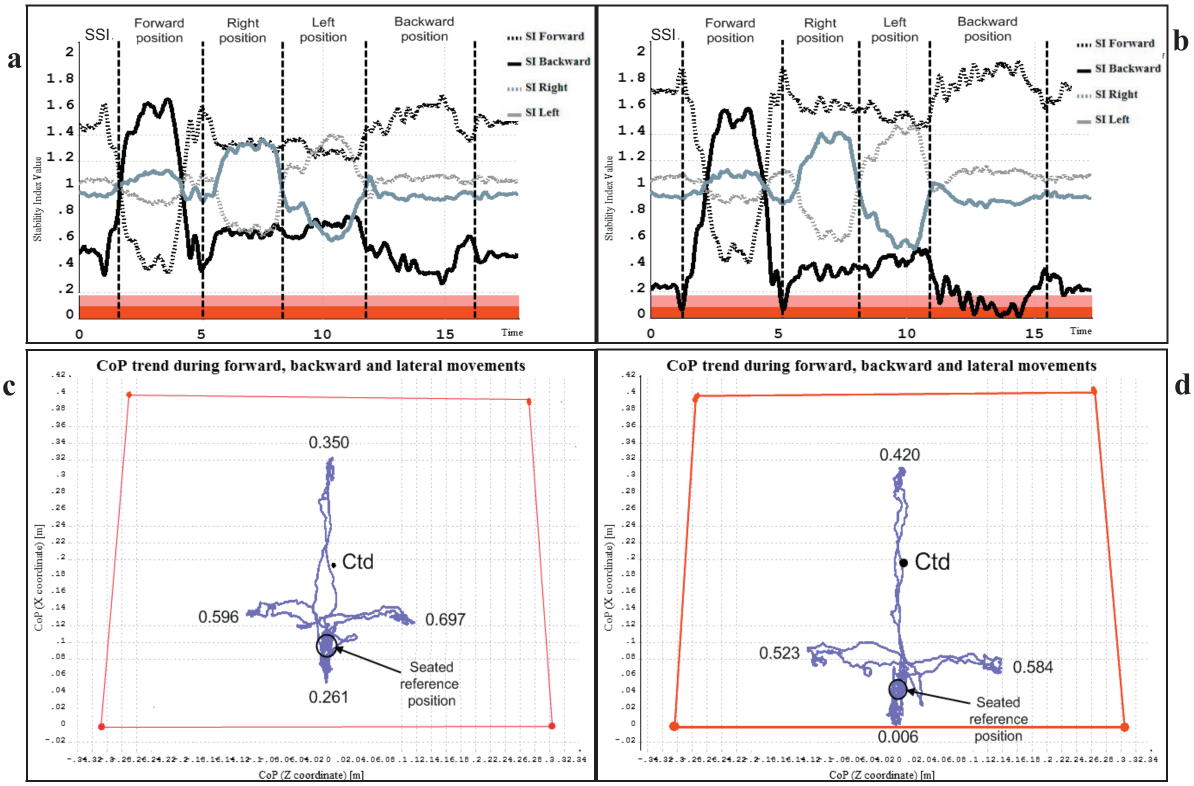

Fig. 3. (a) Example of Stability Index values during FA test performed by male subject; (b) Example of Stability Index values during BA test performed by male subject; (c) CoP trajectory during FA Test; (d) CoP trajectory during BA Test.

5. Discussion

The user-wheelchair system Stability Index has been investigated only with the wheelchair on a horizontal surface: in analogy with previous studies on the topic (Kirby et al. (1995)), the test can be easily performed on a tilting force place to include the effect of the height of the user-wheelchair center of mass. In this configuration the Stability Index can be calculated until the wheelchair wheels touch the ground and the ground contact point have a trapezoid shape. On this regard, the present definition is applicable for any shape of the base of support polygon, so it could also apply when the castor wheels are swiveling, provided that a method for detecting their instantaneous position is available (such as a motion capture system).

The Stability Index was preliminary evaluated only with respect to four static postures that were ideally selected as possible representation of the most extreme unstable posture. However, the daily activities of a wheelchair user include several dynamic actions due to the trunk, head and upper limb mobility that will lead to the possible extension of the present concept of Stability Index towards a Dynamic Stability Index, in analogy with the available ISO standard ISO 7176-2: in this case, also the dynamic effects due to the motion of the wheelchair will have an influence. The Static Stability Index will always correspond to the static reference posture of the subject in the wheelchair.

The Stability Index can give quantitative information about user-wheelchair stability, but the recommended values to be adopted for each user depend on several factors such as user's anthropometry, mobility and degree of activity. In some cases, the rearward Static Stability Index value shall be recommended to have low values in order to facilitate the front wheels lifting for an active user requiring a so called "active" wheelchair. On the contrary, high values of Stability Index in all directions can be recommended to guarantee the highest safety conditions available for an elder user or a user with spasticity. This may lead to introduce a classification of the wheelchairs degree of "activity" based on different ranges of the value of the Stability Index.

6. Conclusions

A new Stability Index was introduced to quantify the degree of stability of a certain user on a certain wheelchair with a specific set of adjustments. The Index was evaluated on a manual rigid wheelchair after asking to two volunteering subjects to assume four postures representative of possible unbalanced situations. The Stability Index assumed a zero value when the wheelchair was close to tipping in the rearward direction.

By combining the introduction of the Stability Index with the user's and clinicians subjective evaluations, an *integrated approach* can be easily carried out in an orthopedic workshop or ambulatory to support the most appropriate wheelchair choice and adjustment for a specific user's anthropometry, mobility and degree of activity. In the same way the Stability Index could be used in a Paralympics training center to set the most appropriate wheelchair setup for disabled athletes in order to reduce the injury risks or to increase the athlete-wheelchair tuning, therefore improving the levels of sport performance.

7. Acknowledgements

Thanks to Marica Pesce and Dennis Da Corte for taking part to the experimental tests at the Department of Industrial Engineering, University of Padova, Italy.

References

ISO 7176-1:1999 . Wheelchairs -- Part 1: Determination of static stability.
ISO 7176-2:2001. Wheelchairs -- Part 2: Determination of dynamic stability of electric wheelchairs.
ISO 7176-11:1999 . Wheelchairs -- Part 11: Test dummies.
Kirby R. Lee, Sampson Maria T., Thoren Fredrik A.V., MacLeod Donald A., 1995. Wheelchair stability: Effect of body position. Journal of Rehabilitation Research and Development 32, 367-372.
Winter David A., 2009. Biomechanics and Motor Control of Human Movement, John Wiley & Sons, 2009.