ANALYSE OF POSTURAL DYNAMIC EQUILIBRIUM IN ELDERLY SUBJECTS DESCENDING A STEP BACKWARDS

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Abstract: The initiation of a movement requires the application of propulsive forces (PF). However, PF constitute a source of perturbation for postural equilibrium. In order to counterbalance this postural equilibrium perturbation, anticipatory postural adjustments (APA) are made. The global aim of this study was to analyse the motor program reorganisation associated to backwards step descent in elderly subjects. Ten adult (AD) and 10 elderly (EL) subjects adopted a stable position on a force plate before stepping down at a spontaneous velocity. An increase in total movement duration (dTOTAL) and a reduction in the anteroposterior impulse at the second foot-off (Ix_{FO2}) in EL subjects relative to AD subjects showed that movement performance was not as good in EL subjects. Such changes are indicative of an alteration in the control of postural equilibrium in EL subjects. The motor strategies used by EL subjects to perform the movement studied was to lengthen APA duration (dAPA) and reduce intensity of the PF at the foot-of (X'_{FO1}) i.e. reduce the intensity of the postural perturbation. During intentional movement, EL subjects lengthened the stance phase duration and minimized the intensity of postural perturbation at the foot-contact and during stance phase by reducing anteroposterior (Rx_{FC1}) and mediolateral (Ry_{FC1}) forces, and the vertical slope of unloading (ULR). The biomechanical parameters used to demonstrate the motor program reorganisation could be used as an index of postural equilibrium instability.

Introduction

The initiation of a movement from a static posture requires the application of propulsive forces (PF), in keeping with biomechanical laws. However, these PF constitute a source of perturbation for postural equilibrium. In order to perform the movement successfully, the nervous system must control the destabilising effect generated by PF generation, that is to say that control of dynamic equilibrium must be involved [1]. To control the postural equilibrium perturbation due to the intentional movement, the central nervous system develops dynamical phenomena before the intentional movement called anticipatory postural adjustments (APA) [2]. As the APA were observed before the intentional movement, they can not result from a reafferentation triggered by the intentional movement, and are instead considered to be pre-programmed. According to Bernstein [3], APA constitute a part of the motor program.

In healthy adult subjects ascending or descending a stair, a greater separation between the centre of mass (CoM) and the centre of pressure (CoP) was measured for stair descend than stair ascent [4] demonstrating a greater instability for stair descent movement, which requires more "balance" compensation [5-6]. Therefore, stair descent represents a challenging locomotor task which may explain why so many falls occur on stairs [7].

As part of the ageing process, there are a number of functional changes in the sensory [8-10] neurological [11-12], and musculoskeletal [13-15] systems. These changes affect one of the main components that is necessary to generate movement, which is the control of postural equilibrium. Degradation of this component requires a reorganisation of the motor process related to the movement execution.

In elderly subjects descending a stair forwards adaptations in locomotor patterns related to stair descent have been analysed [16-18]. These studies demonstrated a motor process reorganisation by measuring a lower vertical clearance of the foot, a lower step length [18], a lower coefficient of friction measured between the foot and the ground [16], and a higher vertical brake impulse [18] relatively to healthy adult subjects.

At present, almost all studies previous published have concerned forwards stair descent. However, although backwards stair descent is a common daily task, only one study has analysed backwards stair descent in healthy adult subjects [8]. Backwards stair descent movement was mainly analysed according a local approach, i.e. in terms of joint moments, muscular power. In order to better understand the motor program linked to a backwards stair descent movement, it is necessary to investigate further. Furthermore, to have a fuller understanding of the dynamics of this complex movement, it is necessary to understand the global biomechanical modifications of the CoM dynamics and to analyse APA, which play an important role in the control of postural equilibrium [1]. However, there is no literature currently available that describes backwards stair descent in terms of CoM dynamics and the APA phase.

 ISSN: 1727-1983 © 2005 IFMBE

The global aim of this study is to analyse the reorganisation of the motor program related to backwards step descent in elderly subjects, in order to identify the strategies used to control postural equilibrium. This study analyses overall movement i.e. the APA and intentional movement in terms of CoM dynamics. More precisely, a comparative study of the postural equilibrium processes between elderly and adult subjects descending a step backwards will be performed in order to extract measures of dynamic stability. Such variables could then be combined with classical static measures of equilibrium extracted from a stabilogram to provide a global balance test.

Materials and Methods

Subjects: Adult (AD) subjects (n=10; mean age = 33.3 ± 7.4 y) and elderly (EL) subjects (n=10; mean age = 73.3 ± 1.5 y) participated in the study, for which all subjects gave their informed consent.

Protocol: The single step backwards movement execution protocol was used: subjects started from a stable upright position before performing a backwards step from the force plate, upon verbal instruction, and remained as stable as possible on the ground for several seconds (Figure 1). Subjects were barefoot, and kept their arms at their sides, while looking down at a cross placed 4 cm from the back of the force plate, in a central position. The movement was performed at a spontaneous velocity.

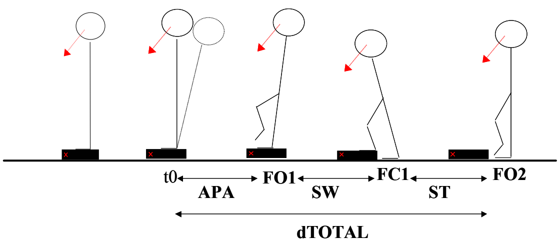

Figure 1: Protocol for backwards stair descent

Data acquisition: An AMTI OR6-5 force plate, measuring 50.8 cm by 46.4 cm was used to collect CoP data (Advanced Mechanical Technology Inc., Watertown, MA, USA). Data acquisition was performed with Protags software (version 4.0, J.-Y. Hogrel, Institut de Myologie, Assocation contre les Myopathies, Paris, France), which was developed under Labview (Version 7.0, National Instruments, Austin, TX, USA). A PCI-MIO16E1 DAQ card was used to collect the signals (National Instruments, Austin, TX, USA), which were sampled at 100Hz. The cut-off frequency of the force plate low-pass filter was set at 10.5 Hz. The data collected consisted of three forces (Rx, Ry, and Fz) and three moments (Mx, My, and Mz), which were subsequently processed for parameter calculation.

Parameter calculation: Extraction of all parameters was performed using Matlab (Version 6.0, The MathWorks Inc. Natick, MA, USA). The location of all temporal events identified was performed automatically, as follows:

The moment at which the APA starts (t0) was detected using the Ry signal. The mean and the standard deviation of Ry measured before the t0 (when the subject was stable) were calculated, with a threshold corresponding to six times the standard deviation. The moment where the threshold was exceeded was taken as t0.

The moment at which the first foot-off from the force plate (FO1) occurred, was detected using the mediolateral CoP signal. The moment was taken as the net break of the Yp before the establishment of the plateau.

The instant of second foot-off from the force plate (FO2) was identified using the Fz signal. The mean of Fz with no subject on the force plate was calculated. FO2 was taken as the first value lower than the mean that occurred between FC1 and the end of the recording.

The instant when the first foot touched the ground (FC1), thus starting the stance phase, was detected using the Fz signal. The Fz signal was examined in reverse, starting from the end of the signal, with differences between successive values of Fz calculated from FO2 to F01, where FC1 was taken as as the point at which Fz stopped increasing.

Measured variables included the durations of the different phases of the step (Figure 2, left side): total movement duration (dTOTAL); delimited between t0 and FO2; APA phase duration (dAPA) delimited between the t0 and FO1; swing phase duration (dSW); delimited between FO1 and FC1; stance phase duration (dST); delimited between FC1 and FO2.

The anteroposterior (X''_{FO1}), mediolateral (Y''_{FO1}) and vertical (Z''_{FO1}) acceleration of the CoM, were deduced from Newton's law: $X''_G = Rx/m$, $Y''_G = Ry/m$ and $Z''_G = Rz/m$, where $Rz = Fz - W$, W is the subject weight, m is the subject's mass, expressed in kilograms. At FO1, CoM velocity was measured: anteroposterior (X'_{FO1}), mediolateral (Y'_{FO1}) and vertical (Z'_{FO1}) CoM velocities were calculated by a simple integration of the acceleration data (Figure 2, right side).

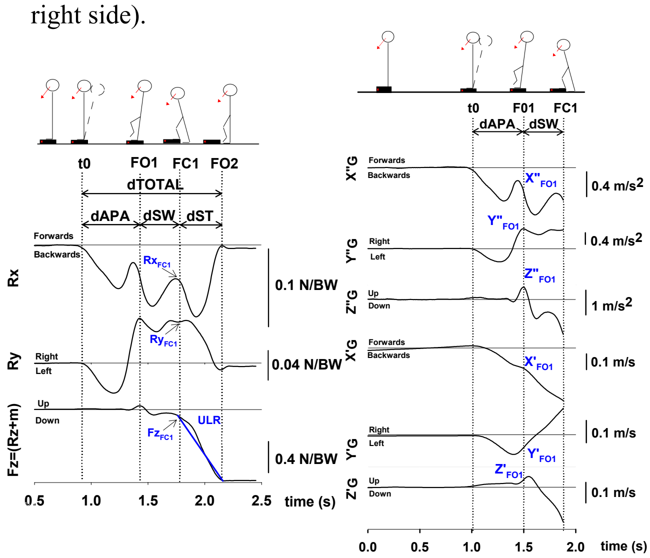

Figure 2: Biomechanical traces for a typical adult subject

At FC1, ground reactions forces normalised by subject weight were measured for anteroposterior (Rx_{FC1}), mediolateral (Ry_{FC1}) and vertical (Fz_{FC1}) axes (Figure 2, left side).

During the stance phase, the slope of the vertical ground reaction forces (unloading rate) was calculated from ground reaction forces and phase durations, as follows:

$$ULR = \frac{(Fz_{FO2} - Fz_{FC1})}{(FO2 - FC1)} \qquad (1)$$

where Fz_{FO2} and Fz_{FC1} are the vertical force values, normalized by subject weight, measured at FO2 and FC1 respectively (Figure 2, left side).

At FO2, impulsion was measured for the anteroposterior axis (Ix_{FO2}) by a simple integration of the anteroposterior ground reaction force data normalised by weight subject.

Statistical analysis: statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). A one-way ANOVA was used to compare results between AD and EL subjects. A *p* value less than 0.05 was considered as an indication of statistical significance.

Results

An example of typical ground reaction forces for an adult subject can be seen in figure 2 (figure 2, left side). At t0, which signals the start of the APA phase, anteroposterior ground reaction forces progress towards negative values. Rx values are negative until FO2 demonstrating that backwards propulsive forces were generated during stair descent.

Examination of the mediolateral ground reaction forces showed that at t0 the ground reaction force moved away from the baseline; reaching a peak during APA phase, followed by a progression towards the opposite direction and second peak at FO1, before returning to baseline values.

The vertical ground reaction trace oscillates from t0 until FC1, thereafter moving towards baseline values. Mean values and standard deviations of the temporal and biomechanical parameters are summarized in Table 1.

Total movement duration (dTOTAL) values were higher for the EL than the AD subjects ($p<0.05$). The longer dTOTAL times were due to longer APA duration (dAPA) and longer stance phase duration (dST) for EL than AD ($p<0.05$). In contrast, swing phase duration (dSW) was comparable between EL and AD (figure 3).

At FO1, with the exception of anteroposterior CoM velocity (X'_{FO1}), which was lower for EL than AD, mediolateral and vertical CoM velocity (Y'_{FO1}) and vertical CoM velocity (Z'_{FO1}) were comparable between EL and AD (see figure 4).

Table1: Temporal and biomechanical parameters measured for adult (AD) and elderly (EL) subjects during stepping down backwards. Data are means and standard deviations. NS: no significant difference; ***: $p\leq0.001$; **: $p\leq0.01$; *: $p\leq0.5$.

Parametres	AD	EL	*p*
dTOTAL (s)	1.60 ±0.30	1.98 ±0.42	**
dAPA (s)	0.63 ±0.11	0.81 ±0.30	*
dSW (s)	0.48 ±0.13	0.47 ±0.20	NS
dST (s)	0.50 ±0.24	0.71 ±0.40	*
X'_{FO1} (m.s)	-0.07 ±0.06	-0.02 ±0.04	**
Y'_{FO1} (m.s)	0.05 ±0.04	0.09 ±0.07	NS
Z'_{FO1} (m.s)	10^{-4} ±0.08	-0.01 ±0.02	NS
Rx_{FC1} (N/BW)	-0.07 ±0.02	-0.04 ±0.01	***
Ry_{FC1} (N/BW)	0.04 ±0.01	0.03 ±0.01	**
Fy_{FC1} (N/BW)	0.91 ±0.04	0.93 ±0.06	NS
Ix_{FO2} (BW.s)	-0.06 ±0.01	-0.04 ±0.01	***
ULR	-0.02 ±0.01	-0.01 ±0.004	***

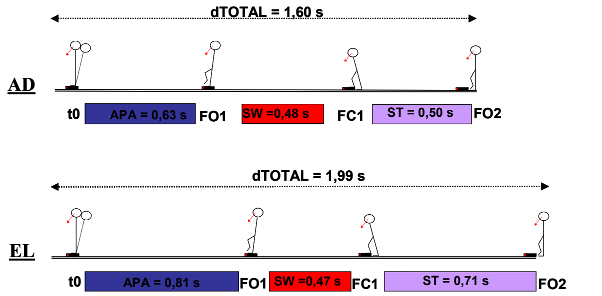

Figure 3: Temporal parameters measured in adult (AD) and elderly (EL) subjects stepping down backwards.

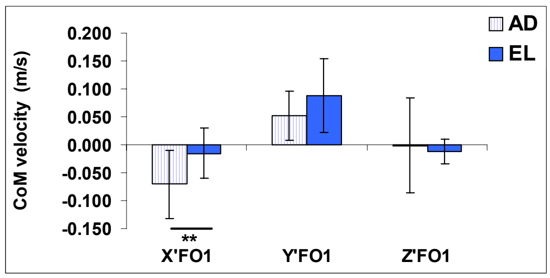

Figure 4: CoM velocities measured for all three axes for adult (AD) and elderly (EL) subjects stepping down backwards.

At FC1, ground reaction forces for both anteroposterior (Rx_{FC1}) and mediolateral (Ry_{FC1}) axes were lower for EL than AD. In contrast, ground reaction forces for the vertical axis (Fz_{FC1}) was comparable between the two groups (Figure 5).

The parameter URL deduced from vertical ground reaction forces measured during the stance phase and dST, was less negative for EL than for AD (Figure 6).

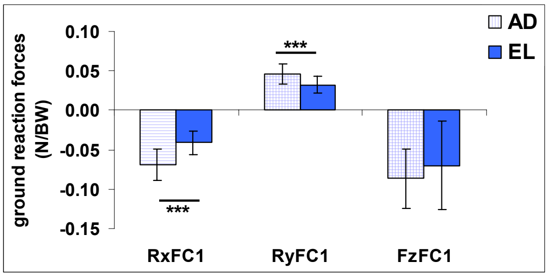

Figure 5: Ground reaction forces measured for all three axes for adult (AD) and elderly (EL) subjects stepping down backwards

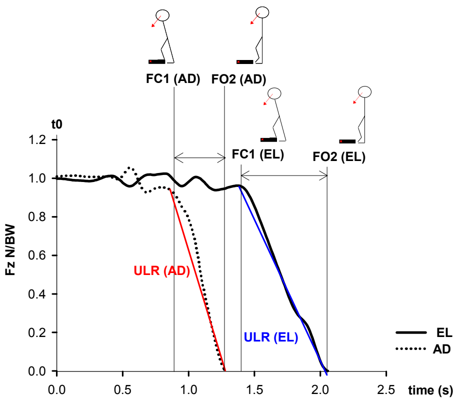

Figure 6: Vertical ground reaction forces and ULR measured in adult (AD) and elderly (EL) subjects stepping down backwards.

Anteroposterior impulsion measured at FO2, Ix_{FO2}, was lower for EL than for AD subjects (see figure 7).

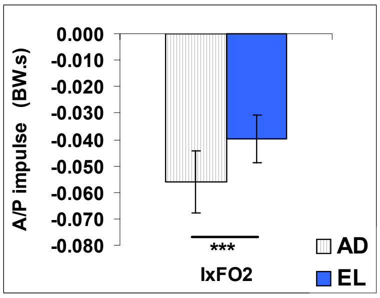

Figure 7: Anteroposterior impulse measured in adult (AD) and elderly (EL) subjects stepping down backwards.

Discussion

Movement execution requires propulsive force (PF) generation that constitutes a perturbation for postural equilibrium. To counterbalance this postural equilibrium perturbation, the central nervous system develops an anticipatory postural adjustment (APA).

Stair descent, demonstrates a greater instability than stair ascent [4] representing a challenging locomotor task, which may explain why so many falls occur on stairs [7]. A number of studies have analysed biomechanical modifications in elderly subjects descending a stair forwards. Despite the fact that backwards stair descent is a common task, only one study analysing this movement has been found [8]. It is necessary, therefore, to evaluate this movement in order to obtain a better understanding of the dynamics of this complex movement.

The aim of this study was to analyse the reorganisation of the motor program related to stair descent backwards in the elderly subjects to identify the strategies used to control postural equilibrium.

Biomechanical parameters measured at the end of the movement can give an indication of the global performance of the movement. Our results showed that dTOTAL was longer for EL than AD, whereas Ix_{FO2} was lower for EL than AD. To descend a stair backwards, EL took more time to generate low anteroposterior propulsive forces, thus decreasing the performance of the movement. In the literature, locomotor movement analysis identified an increase in movement time, associated to a reduction in movement velocity in elderly subjects [19-20], as well as for Parkinson's disease subjects [19, 21-23], subjects with unilateral knee osteoarthritis [24], and for in cerebellar subjects [25], thus demonstrating that these biomechanical modifications were connected with postural equilibrium alterations. Our results were in agreement with the results of the literature confirming that the lower movement performance reached in EL was linked to an alteration of postural equilibrium.

It is widely known that APA constitutes a part of the motor program [3] and parameters measured during the intentional single-step movement reflect the motor program [26-28]. The results showed that dAPA was higher for EL than AD. In contrast, X'_{FO1} was lower for EL than for AD. Parameters measured during the intentional movement showed that dST was longer for EL than AD, Rx_{FC1} and Ry_{FC1} were lower for EL than AD, and ULR was less negative for EL than AD. Theses changes in biomechanical parameters measured on both APA and intentional movement in EL, relative to AD, demonstrated that EL subjects reorganise their motor program in order to perform the movement successfully.

In paraplegic subjects performing a pick-and-place task [29] and for a situation of reduced support base configuration [30], APA are longer, with a correspondingly reduced amplitude. The authors concluded that when the equilibrium is less stable, subjects could not develop APA adapted to the perturbation provoked by movement without an excessive balance risk; so the perturbation created by movement execution was reduced [30]. Our results were in agreement with this finding, demonstrating that EL programmed a longer dAPA in order to better control the postural equilibrium created by the FO1 execution. This movement constitutes a perturbation for postural equilibrium [31-32], therefore a lower X'_{FO1} was programmed to minimize the intensity of the postural equilibrium perturbation at the FO1.

During the stance phase, subjects unloaded the lower limb that was on the force plate to prepare for FO2 and to continue the movement. During this phase, a reduction of Rx_{FC1}, Ry_{FC1} and ULR associated to a longer dST were measured. These results, which were comparable with those measured in elderly subjects descending a stair forwards [17], showed that EL subjects decreased PF generation, i.e. the perturbation of the postural equilibrium created by FC1 to control postural equilibrium. To successfully perform FO2, which represents an additional postural constraint owing to the reduction of the postural base, EL subjects minimise the unloading of the lower limb in contact with the force plate. Therefore, a more cautious unload was performed by EL subjects relative to AD subjects when stepping down.

Conclusion

This study showed that, despite an alteration in the capacity to control postural equilibrium, EL subjects were able to perform a backwards stair descent.

The motor reorganisation developed by EL subjects to successfully perform the movement, was to lengthen dAPA and reduce X'_{FO1} i.e the intensity of the postural perturbation created by the FO1.

To control postural equilibrium during the stance phase and at the FO2, EL lengthened the dST and reduce Rx_{FC1}, Ry_{FC1} i.e. the intensity of the postural perturbation at the FC1. Furthermore, they reduce ULR to perform a more cautious unload of the lower limb in contact with the force plate during the stance phase.

The biomechanical parameters used to demonstrate the motor program reorganisation can be used as index of postural equilibrium instability.

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