# Adaptation of walking ground reaction forces to sudden changes in ground stiffness properties

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***Abstract*— When unexpected stiffness changes of the ground surface occur while walking, the central nervous system needs to apply appropriate control actions to assure dynamic stability. Many studies in the motor control field have investigated the mechanisms of such a postural control and have widely described how centre of mass trajectories, step patterns and muscle activity adapt to avoid loss of balance. However, considerably less attention has been given to the role of the ground reaction forces. The aim of this study was to examine how ground reaction forces adapt when stepping unexpectedly on a soft, compliant surface. Differently from the classical methods to record ground reaction forces based on the use of force platforms positioned at fix locations along the walking path, here we used instrumented shoes, each one equipped with a pair of 3D force torque and motion units under the sole. Preliminary results showed that when stepping over the soft ground participants actively modulated the ground reaction forces under the supporting foot in order to exploit the elastic and compliant properties of the surface to dampen the impact and to likely dissipate the mechanical energy accumulated during the "fall" onto the new compliant surface. Interestingly, this motor strategy emerged already in the first trial, when participants experienced the transition for the first time. We believe that the results presented in this study may be helpful for the development of new control policies to improve stability in humanoid robotic locomotion.**

## I. INTRODUCTION

Human locomotion is a complex dynamic process during which one has to continuously exert corrective actions to react to various perturbations, to maintain balance and continue walking[1].

Many studies have investigated the adaptive mechanisms underlying the control of posture in consequence to expected and unexpected perturbation during several walking tasks such as, for instance, slipping [2], tripping [3] [4] or sudden drop of the support surface [5] [6], [7]. A part of these studies, in particular, has investigated how people react to changes in surface conditions caused by different ground stiffness. Ferris and colleagues [8] found that runners adjust leg stiffness for their first step over a new surface of different stiffness to assure a smooth transition between the two surfaces. Marigold and Patla [9] investigated the control of centre of mass (COM), lower limb dynamics and postural response modulation of muscle activity during unexpected walking transitions between surfaces characterized by different compliance properties. The authors found that the recovery response to the first change of stiffness trial presented muscle onset latencies ranging between 97 and 175ms (supporting theories of a pre-programmed walking strategy) and muscle activity modulation while on the compliant surface. In addition, they also found significant changes in movement dynamics affecting the COM vertical trajectories, aiming to increase dynamic balance. These results were later confirmed by another study [10] that, in addition, described an increase in step length, step width and stability margin on the anterior-posterior direction on the compliant surface to increase the whole-body base of support and to provide in such a way a more effective control on the COM.

The work reported above focusses mainly on kinematics and electromyographic (EMG) activity in response to changes of ground stiffness. Given the difficulty of measuring 3D ground reaction forces and torques on surfaces of varying compliance, there has been, to our knowledge, no reports of kinetics under similar measurement conditions.

The aim of this study was to investigate more in detail the role of ground reaction forces (GRF) in the recovery of balance when an unexpected change of ground stiffness occurs and how GRF adapt in the trials following the first, when the subject understands that this transition will be present. To record GRF under the feet, we used a pair of instrumented shoes equipped with 3D force, torque and motion sensors under each forefoot and each heel. This allowed us to measure the GRF and to calculate centre of pressure (CoP) position under each foot. The use of the ForceShoes (Xsens[1], Enschede, the Netherlands) allowed us to overcome the intrinsic experimental limitations associated with the more classic use of force platforms ([12]), first of all the need of keeping the location of the force platforms fixed during the experiment. We believe that the results provided by this study may not only provide additional interesting insights in the framework of human motor control but also inspire new movement control policies in humanoid robotics.

## II. MATERIAL AND METHODS

### A. *Participants*

Ten participants (five female and five male; age 27±5 years; mass 70±20 kg; height: 1.69±0.08 m) volunteered for this study. Participants had no muscular, neurological, or joint disorders which would affect their performance in

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this study. The experiment conformed to the declaration of Helsinki and written informed consent was obtained from all the participants according to the protocol of the local ethical committee (Ethik-kommission an der medizischen Fakultät der Eberhard-Karls Universität und am Universitätsklinikum Tübingen).

### B. *Compliant platform*

Participants had to walk on an horizontal platform (6m long, 2m wide and 0.3m deep) characterized by two different levels of ground stiffness (see Fig. 1). The first part of the walking surface (4m long, 2m wide) consisted in an elevated wooden platform characterized by a high value of ground stiffness (H in Fig. 1). The second part of the platform (2m long, 2m wide, 0.3m deep) following the wooden part consisted of a soft mattress characterized by a low value of ground stiffness (L in Fig. 1). The whole platform was covered with a uniform tarpaulin in order to hide the ground transition.

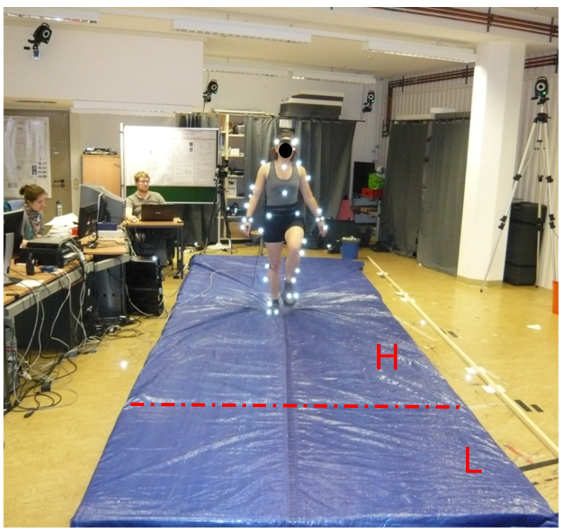



Fig. 1: Compliant walking platform. The first part was characterized by high (H) ground stiffness, the second part by low (L) ground stiffness.

### C. *Protocol*

At the beginning of each experimental trial, participants stood on the edge of the platform at the beginning of the H area and faced toward the other end of the platform. After a 'go' signal was verbally provided by the experimenter and data collection had started, participants had to walk at a preferred pace until they reached the end of the platform, where they had to stop without stepping off. At the end of each trial participants were asked to return to the initial position walking on the normal ground and to prepare for the following trial. Each participant accomplished a total of 10 trials. Participants were not aware of the ground stiffness transition that they would experience. At the end of each trial, before the participant moved back to the initial position, the tarpaulin was pulled from both the lateral sides of the platform to make the whole surface looking flat again to hide any sign of the transition as much as possible. Sample pictures from a typical trial are shown in Fig. 2.

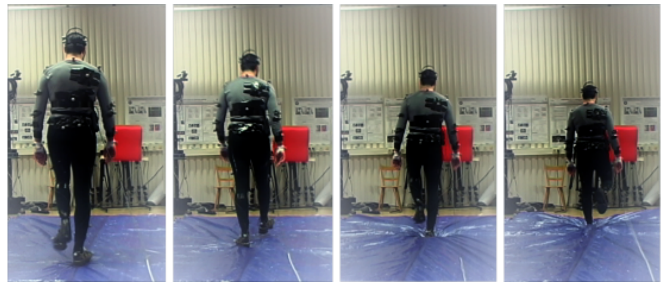


Fig. 2: Example of a walking trial.

Movement kinematics were recorded by means of a (VICON, Oxford, UK) motion capture system with 10 infrared cameras, tracking the positions of 42 reflective markers (2.5cm diameter) with spatial error below 1.5mm. The markers were attached with double-sided adhesive tape to tight clothing worn by the participants. Markers were placed on the locations specified by the Vicon's PlugInGait marker set. Commercial Vicon software was used to reconstruct and label the markers and to interpolate short missing parts of the trajectories. Sampling frequency was set at 100Hz. Transitions were discreetly marked with a Vicon marker on each side of the walkway for processing purposes.

Ground Reaction Forces (GRF) were recorded using a pair of ForceShoes (Xsens, Enschede, the Netherlands), see Fig. 3. Two ForceShoe sizes were available, size 40 or 42 (EU). For details on the system please refer to [11]. The ForceShoe consisted of standard orthopedic sandals equipped with two six degrees of freedom force/moment sensors (ATI-Mini45-SI-580-20, Schunk GmbH & Co, KG) and two MTx (Xsens motion tracker). Each MTx contains 3D MEMS inertial sensors (linear accelerometers and rate gyroscopes) and magnetometers. Sampling frequency was set at 50Hz and synchronized with the VICON by using a link cable and synchronization pulse. Data was recorded with MT Manager ForceShoe 1.7.4.

Fig. 3: ForceShoe system.

## D. Data analysis

*1) Kinematics data:* The positions of the Vicon markers on the feet were used to retarget the force/torque sensors of the ForceShoe in the global (Vicon) frame of reference. The ForceShoe's local reference frame was transformed to the global coordinate frame.

*2) Force data:* The orientation of each ForceShoe is provided directly by each *MTx* attached to the sole. Similarly, the sensors provide direct information about the gravity direction. The two *MTx* sensors divide each ForceShoe into two segments, a forefoot and a rearfoot foot segment. In the rest of this paper, we will use the term 'fs' to indicate any of these segments.

The origin ($\boldsymbol{O}^{\text{fs}}$) of each foot segment is centered on the force/moment sensor. The 3D axes are based on a right hand coordinate system, with $\mathtt{X}$ facing forwards, $\mathtt{Y}$ perpendicular (and pointing left), and $\mathtt{Z}$ pointing upwards.

Forces and moments associated with each sensor can be expressed as

$$\boldsymbol{F}^{\text{fs}} = \begin{pmatrix} F_x^{\text{fs}} \\ F_y^{\text{fs}} \\ F_z^{\text{fs}} \end{pmatrix}_{(\text{fs})} \quad \boldsymbol{M}_{\boldsymbol{O}^{\text{fs}}}^{\text{fs}} = \begin{pmatrix} M_x^{\text{fs}} \\ M_y^{\text{fs}} \\ M_z^{\text{fs}} \end{pmatrix}_{(\text{fs})} \tag{1}$$

where $\boldsymbol{F}^{\text{fs}}$ is the force measured by the force sensor associated with segment 'fs' in the (fs) frame of reference and $\boldsymbol{M}_{\boldsymbol{O}^{\text{fs}}}^{\text{fs}}$ is the moment measured by the moment sensor associated with the same segment in (fs) frame and computed with respect to $\boldsymbol{O}^{\text{fs}}$.

Based on [12], the CoP of each segment can be computed by solving the following equation

$$\boldsymbol{M}_{\boldsymbol{x}^{\text{CoP}}}^{\text{fs}} = \boldsymbol{M}_{\boldsymbol{O}^{\text{fs}}}^{\text{fs}} + \overrightarrow{\boldsymbol{x}^{\text{CoP}}\boldsymbol{O}^{\text{fs}}} \times \boldsymbol{F}^{\text{fs}} = 0 \tag{2}$$

where $\boldsymbol{x}^{\text{CoP}}$ is the CoP position.

Remind that each foot segment is considered as a plane perpendicular to the $z$-axis of the force/moment sensor.

$$\boldsymbol{x}^{\text{CoP}} = \begin{pmatrix} -\dfrac{M_y^{\text{fs}}}{F_z^{\text{fs}}} \\ \dfrac{M_x^{\text{fs}}}{F_z^{\text{fs}}} \\ 0 \end{pmatrix}_{(\text{fs})} \quad \boldsymbol{M}_{\boldsymbol{x}^{\text{CoP}}}^{\text{fs}} = \begin{pmatrix} 0 \\ 0 \\ M_z^{\text{fs}} \end{pmatrix}_{(\text{fs})} \tag{3}$$

On H, all the ForceShoe segments in contact with the floor are coplanar with the ground. Thus in order to obtain the CoP under the foot, it is easy to move every torque to one common point and then use (3) to compute the desired CoP.

On L, all the ForceShoe segments in contact with the soft mattress are not at the same altitude nor in the same orientation. Thus in order to compute the CoP under the foot, we chose to express it in a plane parallel to the surface H. Then we had to express every torque with respect to one common point in this plane and use (3) to compute the projection of the CoP on a single plane.

All reaction forces were normalized with respect to the average vertical gravitational force measured while standing (body mass $\times$ gravity acceleration $g = -9.81\text{m/s}^2$).

With the aim of studying the reactive responses to an unexpected change of ground stiffness and to investigate possible effects of practice on the modulation of the GRF we considered the first, second, fifth and tenth trials for analysis. For each trial, we analyzed the temporal evolution of the vertical component of the GRF associated with the transition step. More specifically we analyzed the GRF under the last footstep that, during the walk, struck on the H area of the platform and the first footstep that struck on the L area. For each foot we quantified the amplitude of the two main force peaks, one associated with the first strike of the first foot-floor contact of the foot with the given surface and the second one associated with foot rolling and ankle plantar flexion in the last part of the stance phase when the ankle joint is extended to provide forward acceleration to the whole-body to move forward. For each trial and each foot, we also quantified the maximum CoP displacement along the direction of motion. To standardize the displacements of the CoP across subjects, we divided the amplitude of each displacement by the distance between the marker on the right heel of the participants and the marker positioned on the tip of the right ForceShoe.

## E. Statistics

All statistical analyses were accomplished using IBM SPSS Statistics, Version 22.0. Two-way repeated measure ANOVAs were used to investigate the effects of ground stiffness and experience on the amplitudes of the two main peaks of vertical GRF and CoP displacements under the feet prior to or following the ground transition. Mauchly's test was used to validate the sphericity. When sphericity was violated a Greenhouse-Geisser correction was used. Post-hoc analysis was conducted by using Fisher's Least Significant Difference (LSD) test when necessary and appropriate. The level of significance was always set at $\alpha = 0.05$.

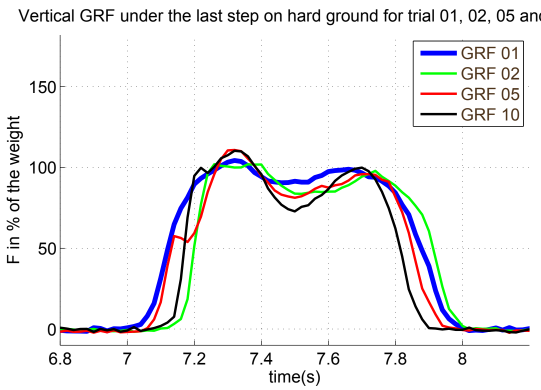
# III. Results

All participants successfully walked over the transition without loosing their balance. We were particularly interested in examining how participants reacted to the change of ground stiffness during their first experimental trial, when they still were not aware of the transition. However, in order to investigate possible learning effects appearing over the trial, we also analyzed the GRF and CoP displacements of the second, fifth and tenth trial.

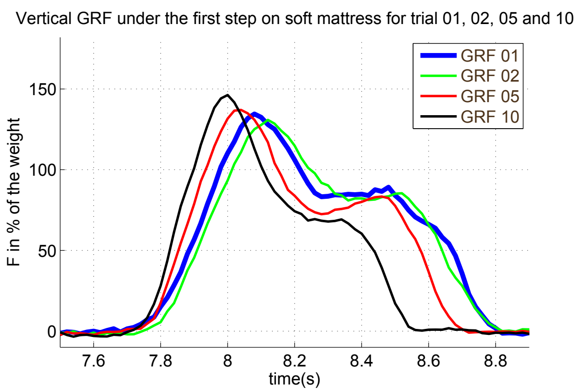
## A. Vertical GRF

Fig. 4a represents the vertical GRF pattern on H. This is the last GRF before the transition was encountered. As trials progressed from 1 to 10 the double peak became more apparent, with the double stance dip in the GRF decreasing more with each trial, as can also be seen in Fig. 5a.

Fig. 4b shows the GRF pattern of the contralateral foot in the same experiment. This foot is experiencing L (as a direct follow up of H represented in Fig 4a). The trends observed here are the clear differences in peak amplitudes between large peaks at foot flat (landing) compared to the peaks just before push-off, as can also be seen in Fig. 5b. Furthermore, one can observe the increase in amplitude occurring slightly earlier in the cycle as the trials progressed from 1-10.




(a) Last step on hard ground




(b) First step on soft mattress

Fig. 4: Example of vertical Ground Reaction Forces (GRF) under the foot stepping (a) before and (b) after the transition from hard ground to soft mattress. The trials are time-aligned in order to align the first peak of the last step on hard ground.

A 2x4 ANOVA with stiffness (H and L) and practice (1st, 2nd, 5th and 10th) as between-subjects factors revealed a main effect of the stiffness on the amplitude of the first peak, $F(1,9)=56.26$, $p<0.001$, but not of practice, $F(3,27)=2.43$, $p=0.87$. This was qualified by an interaction between stiffness and practice, $F(3,27)=3.43$, $p=0.031$. Post-hoc analysis using LSD test indicated that the first peak on the L surface was significantly higher than the one on H ($p=0.027$). Similarly, for the second peak a main effect of the stiffness on the amplitude was found, $F(1,9)=56.26$, $p<0.001$, together with a main effect of practice, $F(3,27)=7.65$, $p=0.001$. These main effects were however not qualified by an interaction between the factors, $F(3,27)=0.678$, $p=0.57$. Post-hoc analysis revealed that the second peak on the L surface was significantly lower that the second peak on H ($p<0.001$) and that the amplitude of the second peak on L decreased significantly over trial (only the average peak values associated with the 2nd and 5th trial were not statistically different, $p>0.05$, for all the other comparison it was $p<0.05$).

### B. CoP displacement

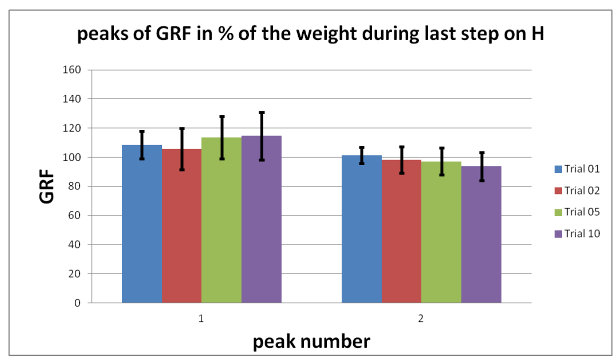
We computed the CoP under each foot in order to compare their distance travelled. In Fig. 6, we can see that the CoP distance under the last foot standing on H increased over the trials when almost constant under the first step standing on L. We can also observe that during the two first trials that the CoP length is longer on L than on H of almost 10 % while almost similar for the fifth and tenth trials.

ANOVA revealed a main effect of the ground stiffness on the average CoP displacement under the foot, $F(1,6)=20.90$, $p=0.004$, while practice had no effect, $F(1.531,9.185)=0.579$, $p=0.536$. The main effect of the softness was not qualified by an interaction between the factors, $F(1.651,9.906)=0.33$, $p=0.687$. Post-hoc analysis revealed that the CoP displacement under the foot on the H surface was significantly shorter that the displacement on L surface ($p=0.004$).

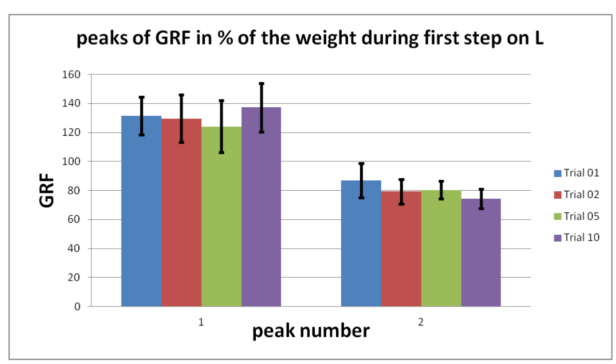
## IV. Discussion

Walking stability can be threatened in everyday life by various external perturbations such as, for instance, an unexpected change of the mechanical features of the walking surface. The goal of this study was to investigate what motor strategies are commonly used to avoid loss of balance when an unforeseen transition from a hard to a soft surface occurs during locomotion.

Some previous studies investigated already the mechanisms underlying the unexpected transitions on a soft surface. For instance Marigold and Patla [9] found that when stepping




(a)




(b)

Fig. 5: (a,b) Vertical GRF peak height

on a compliant surface the central nervous system modulates both COM trajectories and EMG activity to maintain dynamic stability. However, our study is to our knowledge the very first one that has tried so far to characterize such a walking transition analyzing systematically the GRF and CoP displacements under the feet. Our preliminary results suggested that participants might take advantage of the mechanical properties of the soft surface to counteract the unexpected perturbation. The increased amplitude of the first GRF peak under the foot on the soft surface can be explained with an increase of COM vertical acceleration due to the the longer vertical distance covered by the COM when "falling" onto the soft surface. Similarly to us, van Dieën and colleagues [5] described that, when an unexpected change of ground level occurs, GRF on the landing lag are mainly dominated by the initial impact on the lower ground. Counter to the expectation, we found that the second GRF peak on the soft surface was smaller than the second peak under the foot on the hard surface. This result is surprising because it is apparently in contradiction with the other results that we found, which revealed that the CoP horizontal displacement was longer under the foot on the soft surface than under the one on the hard surface. One would expect indeed that, when the CoP displacement increases, also the propulsive force to accelerate the COM forward should increase, determining consequently also an increase of the vertical GRF. In normal walking and running indeed it was already shown that all GRF increase if walking or running velocity increases [13]. These apparently contradicting results may however be explained instead as the outcome of a complex control strategy aiming to dissipate mechanical energy and stabilize posture by exploiting the elastic properties of the compliant surface. Very interestingly we found also that the responsive behavior described above occurred already during the first trial, when participants were still not aware of the transition, and it was tuned during the subsequent trials (the amplitude of the second peak decreased and peaked earlier on L, while first peak increased and peaked earlier). At the contrary we did not find any effect of practice on the GRF under the feet on the hard surface. These findings together suggest a possible switch of control strategy at the time of the transition.

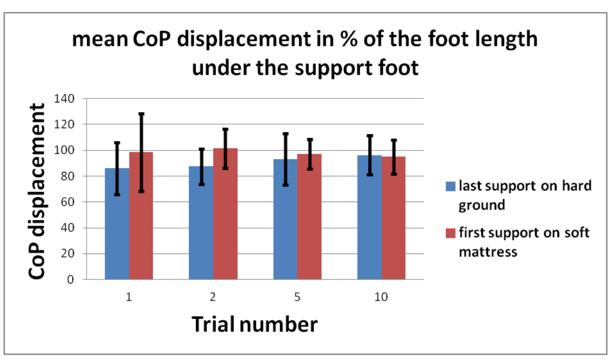



Fig. 6: CoP displacement under the support foot for each trial.

Although any interpretation of the changes underlying the control of locomotion during the transition is delicate, it can be however speculate that the control organization changes from a less stable open-loop control when walking on the hard surface to a more complex closed-loop organization in which, once stepping on the soft surface, the afferent feedback information is used to elicit the correct postural response to assure dynamic stability.

Although the results reported in this study are interesting and provide new experimental evidence on the modulation of the GRF and of the CoP under the feet when a surface transition occurs, we are aware that the current analysis has some limitations. First of all, only the transition step has been analyzed. We plan therefore to extend the analysis also to the step anticipating and to the one following the transition. This will allow us to infer more about possible changes in walking velocity, step length and ankle torques. In second, we did not report neither any kinematic analysis of the COM trajectories nor any inverse dynamic analysis to estimate the torques at the different body joints. These analyses will allow us to validate the main hypothesis that the results of this study suggest, that is that participants exploited the compliant properties of the soft surface to dissipate mechanical energy.

## V. Conclusion

In this study we provided experimental evidence regarding the possible strategies that people adopt when unexpectedly stepping onto a soft surface to preserve dynamic stability and avoid loss of balance. Although additional analyses are needed to understand better all the mechanics of the transition, our preliminary results show that participants modulate the GRF to likely dampen the acceleration that the whole-body COM gain because of the transition on the soft surface.

## Acknowledgements

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