05DHM-45

EFFECT OF RESTRICTIVE CLOTHING ON BALANCE AND GAIT USING MOTION CAPTURE AND STABILITY ANALYSIS

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ABSTRACT

The effect of restrictive clothing on functional reach and on balance and gait during obstacle crossing of five normal subjects is presented in this work using motion capture and stability analyses. The study has shown that restrictive clothing has considerably reduced participants' functional reach. It also forced the participants to change their motion strategy when they cross-higher obstacles. When crossing higher obstacles, the participants averted their stance foot, abducted their arms, flexed their torso, used longer stance time, and increased their hip angle in the medial-lateral (Rolling) and vertical (Yawing) directions. The stability analysis of a virtual human skeletal model with 18 links and 25 degrees of freedom has shown that participants' stability has become critical when they wear restrictive clothing and when they cross higher obstacles.

INTRODUCTION

The study of human factors and behaviors and their interaction with their living/working environments is a major area of research in diverse fields. Examples include ergonomics, physiological, psychological, and balance and gait studies. The main objective in most of these works is to enhance human safety and performance.

In many applications such as rescue efforts and war zones, people are obliged to wear restrictive clothing to protect them from hazardous environments. While these suits provide the protection requirements, they should also have minimal effects on people's performance. The effect of clothing on human posture, balance and gait can be considerably important, especially when the protective suits hinder body's' motion. Examples include space applications and war zones.

There have been many studies toward this end. Punaxillia et al (1), for example, showed that fire workers protective suits have significantly impaired their postural and their functional balance, specifically when the workers hold heavy rescue equipments. In another study, Egan et al (2) assessed the effects of wearing chemical protective clothing on workers static postural sway after a predefined training exercise. Cloth properties such as weight can be another factor that affects balance and gait of people. For this reason, physical therapists for example, use heavy clothing as part of their therapy. One application is the case of stroke patients (3). Another application is in the military arena where the effect of body armors and loads on soldiers' movement and performance has been an active research area (4, 5). In general, restrictive clothing can impose constraints on the relative joint angle limits of the person, and hence obstructs his/her movements. This issue becomes vital in disaster scenarios. Such scenarios are normally associated with rubbles on the floor. While time is a crucial factor in such scenarios, restrictive clothing may restrain people from conducting their normal motion and hence, cause them to select other feasible motions that could be inefficient and probably unsafe. Therefore, the effect of restrictive clothing on people's performance should be considered in studies involving human efficiency and safety.

While studies in cloth modeling and the effect of clothing on humans' performance are still in their infancy, motion capture techniques represent alternative approaches toward this end. The idea behind using motion capture systems is now well established and is being used in many applications. These include balance and gait analysis (6, 7), biomechanics studies (8, 9, 10, 11), anthropometry (12, 13), ergonomic design (14, 15, 16), athletics studies (17, 18), and potential usages in psychiatry (19). Motion capture systems have been shown to be accurate, repeatable, and consistent (20). Motion capture can also be used as a realistic guide in adjusting or quantifying some parameters that play important role in cloth modeling formulation. For example, motion capture can be used to quantify the effect of clothing on the range of movement of the relative joint angle limits for ergonomic applications.

Studies in gait analysis on the other hand have shown that precise gait measurements are essential tools toward finding subtle changes in gait parameters (21, 22). These subtle changes can have significant roles in understanding the mechanism of imbalance in people. For example, precise gait analysis was able to detect subtle alternations in balance in traumatic brain injury patients at the time when clinical exams and scales (Tinetti Balance Scale) did not demonstrate a significant difference between the patient population and normal control subjects (21, 22). One way to achieve precise and extensive gait parameters acquisition is to use modern motion capture systems that are based on infrared cameras and reflecting markers attached on the patient's body

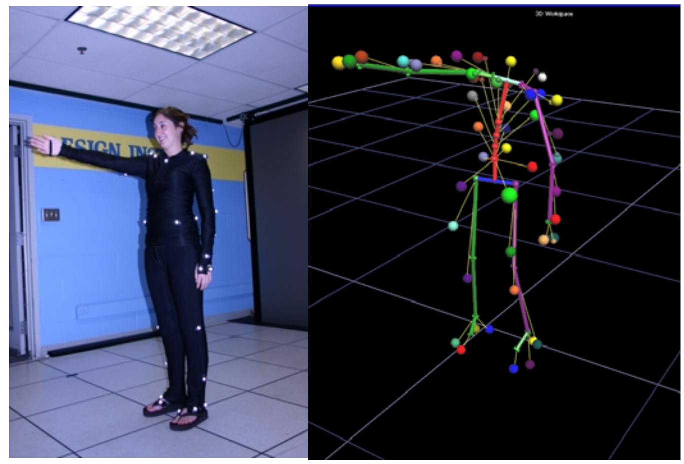
This paper is a part of a major work at the Virtual Soldier Research (VSR) at the University of Iowa with the objective of obtaining realistic clothing models for our virtual human model Santos. The specific intention in this work is to understand the mechanism of restrictive clothing on the performance of normal people and seek key parameters pertinent to the effect of such clothing on posture, motion planning, and stability analysis. These parameters will be then integrated into the analytical clothing model of the virtual human model to enhance the capability of the model with rational posture and motion planning.

Two approaches are presented in this work toward finding measures to quantify the effect of restrictive clothing on the stability and on the motion strategy of five healthy participants. The first approach is based on clinical techniques where studies are normally associated with standard subjective tests to measure balance and gait impairments, such as functional reach test (27) and obstacle crossing (28, 29, 30, 31). The second approach is an engineering one and is based on utilizing dynamics stability analysis of a skeletal structure human model to quantify/qualify the stability of people under different walking scenarios. In both approaches, motion capture system is utilized to collect precise data of posture and motion of the participants when they wear normal and restrictive clothing.

In the body of this article, a preliminary description of the motion capture system used in this work is first presented. The second section describes the skeletal structure of the human model for the dynamic analysis. The focus in the third section is on the effect of restrictive clothing on the functional reach. The forth section presents the effect of restrictive clothing on the stability and motion during obstacles crossing. Finally, this article ends with discussion and some concluding remarks.

MOTION CAPTURE PROCESS

Fig. 1 illustrates the procedure of using motion capture system at the VSR lab, University of Iowa. First, the motion of a person wearing a motion capture suit, where a number of markers are attached to his/her body, is recorded using infrared cameras (Fig. 1a). Second, the motion is then mapped onto a skeletal human model (Fig. 1b), which is built inside the motion capture software. The last step involves the post-processing operations, where various gait parameters such as stride length and relative joints angles are characterized.



(a) (b)

Figure 1, (a) A participant wearing a motion capture suit (b) Vicon skeletal human model,

In this work, eight cameras Vicon motion capture system is used to track the postural reach and the movement of five normal participants. Each participant wears normal clothing in one event and restrictive clothing in the other. In normal clothing, the participants wear a jeans pant and a T-Shirt, while in the restrictive clothing, the participants wear leather jacket and another jeans pant over the normal clothing. In both normal and restrictive clothing, the participants wear a motion capture suit (Fig.1a) over their clothing. The motion capture suit has sticking properties, which facilitates the process of attaching markers on the participants' bodies. In this study, thirty reflected markers are attached to the participants' bodies in well-defined areas, such as the shoulders, the elbows, the knees, the ankles, and the spine joints. Fig. 1a shows the locations of the markers on the participant's body.

In this work, the participants are instructed to perform a number of postures and movements to show the effect of clothing on their ability to conduct standard tasks pertinent to that of the emergency workers. For example, the participants are asked to perform postural reach out for objects to their side, front, and ceiling. The participants are also instructed to walk inside the motion capture lab for 3 meters with normal walking in one test and crossing obstacles with different heights (15, 30, 45, and 53 cm) in other tests.

FUNCTIONAL REACH

Studies in biomechanics and medicine have shown significant correlations between functional reach and balance in patients. Based on such hypotheses, they created standard tests to assess people's balance and their tendency to fall. Several performance balance measures are now clinically available to evaluate and identify fall risk in people. Examples are Tinetti Balance Measures (23), Berg Balance Scale (24), Timed Up and Go test (25), Step test (26), Functional Reach test (27), and Lateral Reach test (27). The goal of these measures in general is to obtain simple tools to predict fall and to assess and prognosticate. These measures, while subjective, have shown considerable success in some applications in terms of their ability to identify the deviation in patients balance from normal. For example, they showed that people with fall history have relatively smaller reach ability when compared with their matched aged normal; in addition, they found significant correlations between the reach distance and balance and fall history of the participants.

STABILITY ANALYSIS AND VIRTUAL HUMAN MODEL

Virtual Human Model

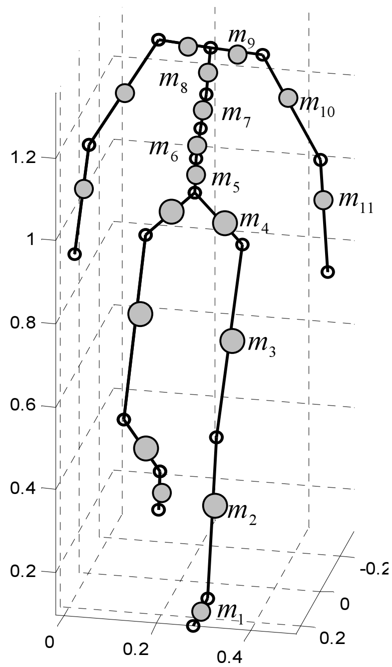


Figure 2, The numerical model for a virtual human has 18 links and 25 degrees of freedom. The grey circles represent the concentrated mass of each link

The virtual human model for the numerical stability analysis used in this work is a skeletal structure that has 18 links and 25 degrees of freedom in 3D space (Fig 2). In Fig. 2, body joints are denoted by empty circles and the concentrated masses of the body links by solid grey circles. The concentrated masses ($m_1 \sim m_{11}$) are given in Table 1. The masses are symmetric with respect to Sagittal plane.

Table 1. The mass distribution of the body [Winter (31)]

$m_1 / \overline{m}$	1.86 %
$m_2 / \overline{m}$	5.95%
$m_3 / \overline{m}$	12.80%
$m_4 / \overline{m}$	0.00%
$m_5 / \overline{m}$	0.00%
$m_6 / \overline{m}$	0.00%
$m_7 / \overline{m}$	0.00%
$m_8 / \overline{m}$	73.0%
$m_9 / \overline{m}$	0.00%
$m_{10} / \overline{m}$	3.59%
$m_{11} / \overline{m}$	2.82%

($\overline{m}$ is the total mass)

Lateral Stability Measure

In general, stability is defined as the ability to keep body posture upright. When a biped is tipping on ground in forward or backward directions, one can stop falling by stepping forward or backward (anterior-posterior falling). Also, when a biped is tipping left while being supported on right foot, it may stop falling by stepping with one's left foot in the left (medial falling). But when a biped falls to the left while one's support is the left foot, then stepping does not prevent the fall (lateral falling). Thus, lateral falling is the most critical instability in crossing-an-obstacle when one lifts up one's leg to avoid collision with the obstacle.

In this study, it is proposed that the static stability criterion applies to the lateral motion such that, during stable state, the Projected Center of Mass (PCOM) would not go outside the lateral boundary of base of support (BS), thus preventing the initiation of lateral falling. The BS refers to the sole part that is in contact with the ground in single support case and, to a convex polygon that encloses such sole parts in double support case. Such static stability can be measured through the relative position of the PCOM (point $\mathbf{P}$ in Fig. 3) to the lateral boundary of BS (x-axis). The lateral boundary of BS can be identified by the location of foot-ball $\mathbf{Z}$ of a supporting foot, to which the origin of x-y coordinate is attached. A point $\mathbf{G}$ is the center of mass of the virtual human.

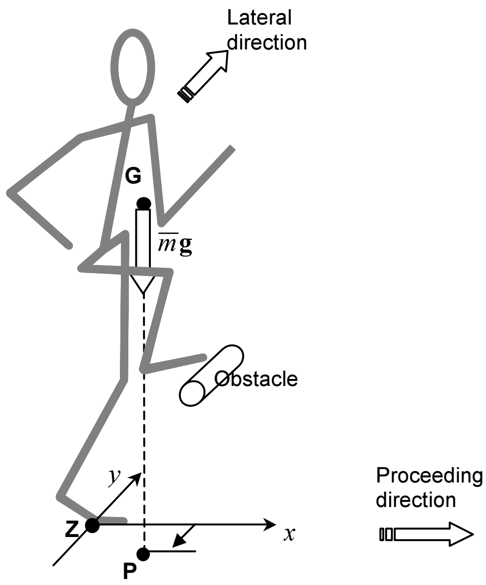


Figure 3, A virtual human crossing over an obstacle by lifting the right leg and stepping on the left foot.

EXPERIMENTAL RESULTS

Effect of Restrictive Clothing on Functional Reach

In this work, many experiments are conducted to find the maximal reach a person can conduct from a bilateral stance position. The participants stand with their feet apart with a distance comparable to their shoulder width. Then, they are instructed to reach an object in front, side, and ceiling with their feet remaining on the floor to the moment when they are on the verge of lifting one or both feet off the ground. In all reach tasks, the participants are instructed to abduct their arm 90 degrees and then point it in the direction of the reach. For example, in the frontal reach, the participants first abduct their arm sideways 90 degrees and then point in the direction toward the front of them. The frontal reach distance is obtained by measuring the relative positions of the marker attached to the participant right hand and the marker attached to the participant right foot/toe. Fig. 4 demonstrates the effect of restrictive clothing on the reach distance in the front, side, and ceiling directions. The y-axis in this figure represents the percentage difference in the reach distance between the person who wears normal clothing (NC) and the person who wears restrictive clothing (RC), divided by the reach distance when the person wears normal clothing (NC). Each block in this figure reflects the behavior of one participant. The figure clearly shows a significant reduction in the functional reach when the participant wears restrictive clothing versus normal clothing. It should be mentioned here that the effect of restrictive clothing on participant's functional reach in this work is relative and proportional to the available clothing which the participants used. In this regard, some participants wear clothing that has more restriction than

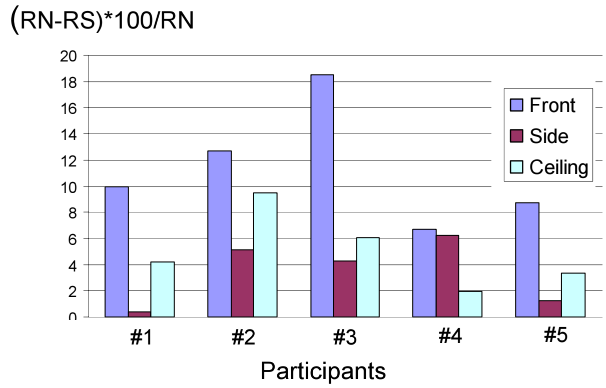


Figure 4, Percentage difference between participants reach when they wear normal clothing (RN) versus restrictive clothing (RS).

those wear by other participants. The effects of these differences can induce some inconsistency in the resulting data. It is therefore very important for future studies to conduct the tests using standard suits designed for specific application with real people who are engaging in such tasks. In such case, it becomes possible to obtain precise data for the specific cloth and then to impose its restriction as constraints on the virtual clothing model for such application.

Effect of Restrictive Clothing on Stability during Obstacle Crossing

In this work, our main objective is to capture subtle changes in the balance and gait of normal people when they wear restrictive clothing. In this section, five normal participants are instructed to walk normally inside the motion capture lab for three meters in one test, and then they are instructed to cross obstacles of different heights (15, 30, 45, and 53 cm) in other tests. The obstacles are a set of angled-bar connected together by 15 mm bolts. They form a box-like structure that has a width of 30 cm and an adjustable height. The participants wear normal clothing in one set of tests and restrictive clothing in the other.

Effect on stance time

The number of parameters associated with participants crossing the obstacles is relatively large. For example, participants change their motion strategy when they cross higher obstacles and when they wear restrictive clothing. One reason for this change is their inability to cross the obstacles as they normally proceed with normal clothing. This is because their relative joint angles are reduced due to the restrictive clothing. Therefore, the participants are forced to change their motion strategy. For example, they cross the obstacles by twisting their stance foot outward (avert their foot) and their body accordingly in the Yawing direction. Of course, this behavior is relative and depends on the participant's leg height and the restriction imposed by the restrictive clothing.

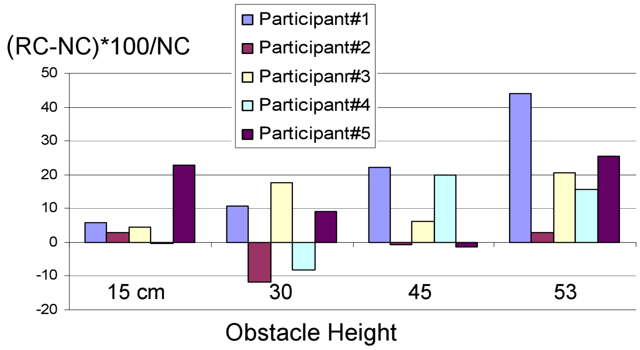


Figure 5, Percentage difference between the relative stance time for the leading leg with restrictive clothing (RC) to normal clothing (NC) with obstacle's height of four cases (15, 30, 45, and 53 cm)

Biomechanical and clinical studies have shown that stance time has significant implication on people balance and gait (22, 28). With the alternative crossing strategy, the participant stance time when the leading leg crosses the obstacles, increases in most cases as shown in Fig. 5. Similarly, the stance time when the trailing leg crosses the obstacles steadily increases as shown in Fig. 6.

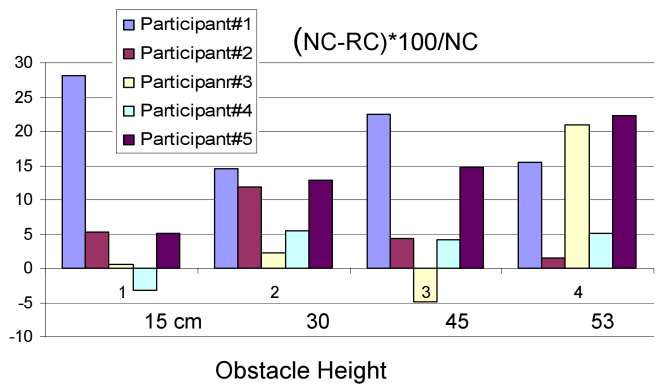


Figure 6, Percentage difference between the relative stance time for the trailing leg with restrictive clothing (RC) to normal clothing (NC) with obstacle's height of four cases (15, 30, 45, and 53 cm).

Effect on hip angles

Previous studies in balance and gait have shown that hip rolling in the medial-lateral direction presents a good measure of the tendency of a person to fall (21, 22, 29, 30). In this case, the person's center of mass will deviate beyond his/her BS, and thus, the person becomes prone to falling in this direction. It is because he/she becomes incapable of taking another step to retrieve his/her stability.

In this work, the focus is on the changes in this hip angle in the medial-lateral direction, which obviously increases with increasing obstacle heights and with the existence of restrictive clothing (Fig. 7). Nevertheless, in some cases, especially when the participant is not capable of conducting the crossing process in normal ways, he/she tends to change the crossing strategy and twist the hip around the vertical axis of the floor (yawing motion). For convenience, the normal crossing is designated as Mode I and the crossing that accompanies yawing as Mode II. In Mode I crossing, the knee position is even higher than the foot position while in Mode II crossing, knee and foot are at almost same height. So, when the obstacle is too high or body motion is restricted by special clothing, Mode II crossing is the only feasible way of motion. In Mode I, the supporting foot is in progression (forward) direction, while it is "open" – that is, facing sideways in Mode II (Fig. 8).

Increasing the yawing angle in Mode II may introduce a feasible crossing strategy for a higher obstacle, but in general this strategy is inefficient and takes longer time. This can be explained by looking at the hip angles of participant # 1 in Fig 7a. In this case, the participant uses significantly larger relative stance time (Fig. 5) than that of other participants. Fig. 8 shows Vicon motion capture pictures for different participants when they cross the 53 cm obstacle. The pictures show the general trend, where a significant change in the rolling and yawing angles are associated with restrictive clothing. One can also check that Mode II crossing is associated with restrictive clothing by looking at the supporting foot orientation. Moreover, it is very clear from Fig. 8 that all participants have abducted their arms and bent their upper torso toward the anterior direction (flexion) when they wear restrictive clothing. This behavior is a clear evidence of the instability associated with restrictive clothing.

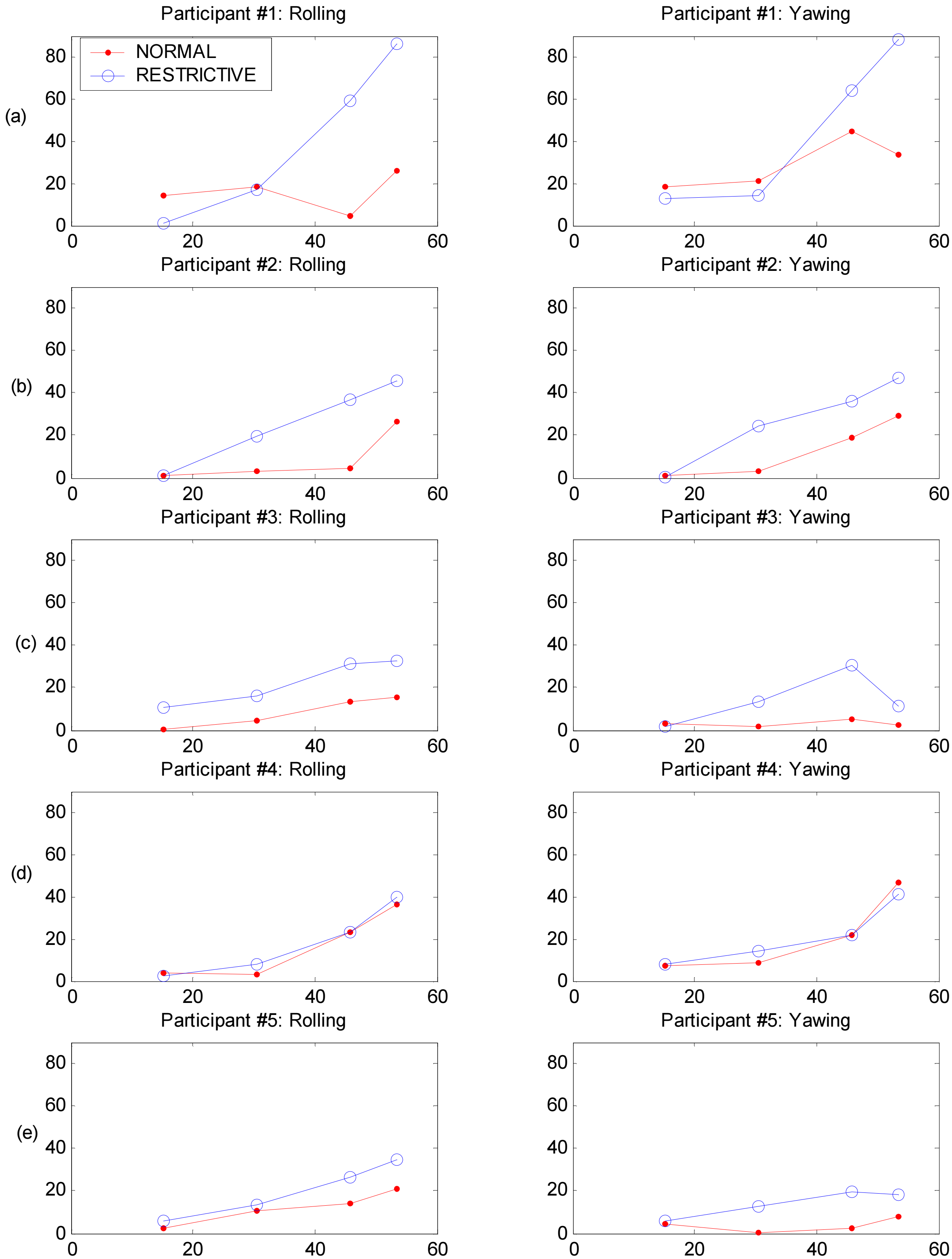
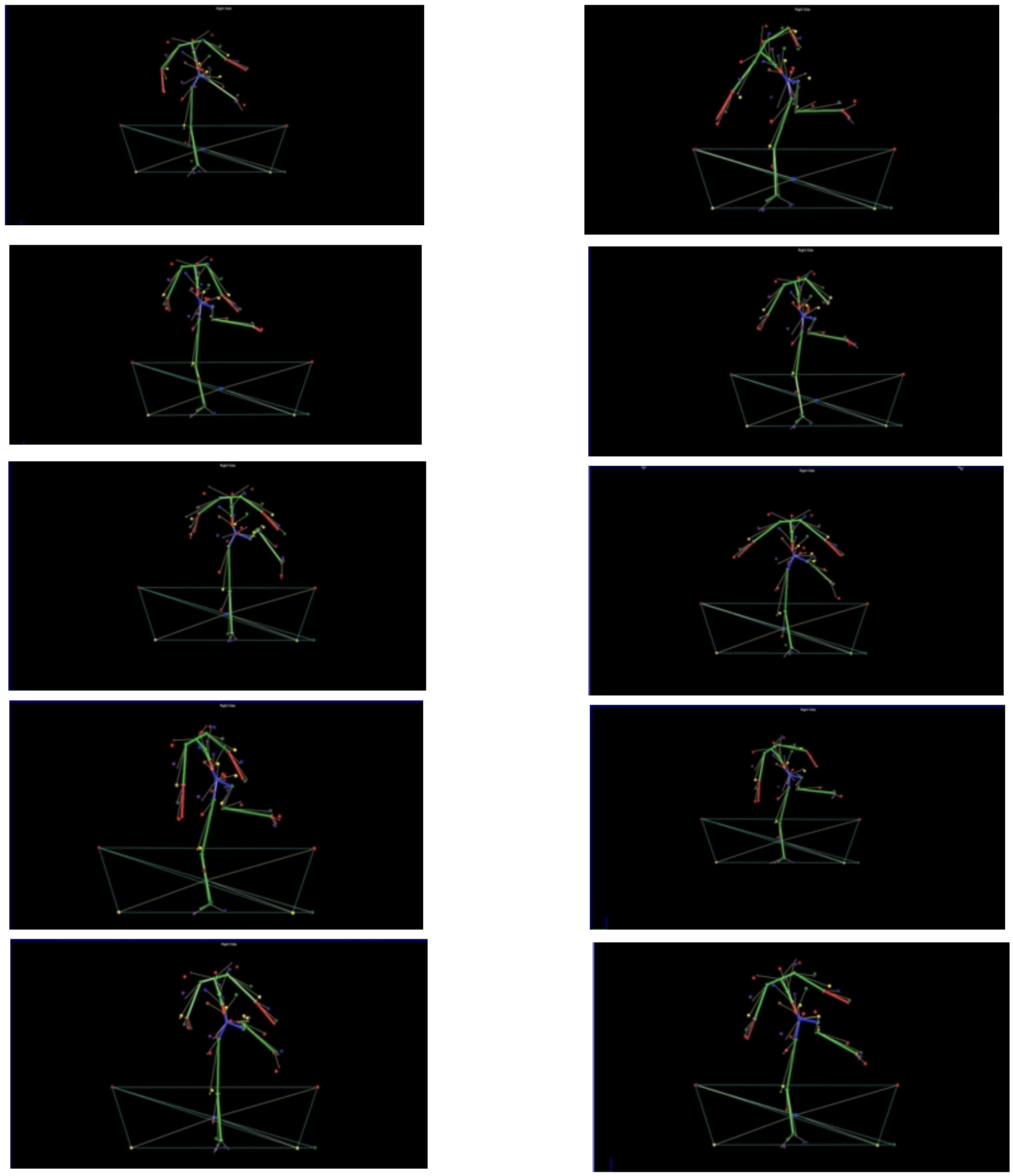


Figure 7, Hip angles in the rolling (medial-lateral) direction and twist (yawing direction) when crossing obstacles with heights (53cm): (a) particiapnt#1, (b) participant#2, (c) participant#3, (d) participant#4,and (e) participant#5.



(a) Participant#1

(b) Participant#2

(c) Participant#3

(d) Participant#4

(e) Participant#5

Normal Clothing

Restrictive Clothing

Figure 8, Participants motion when crossing an obstacle with 53 cm height

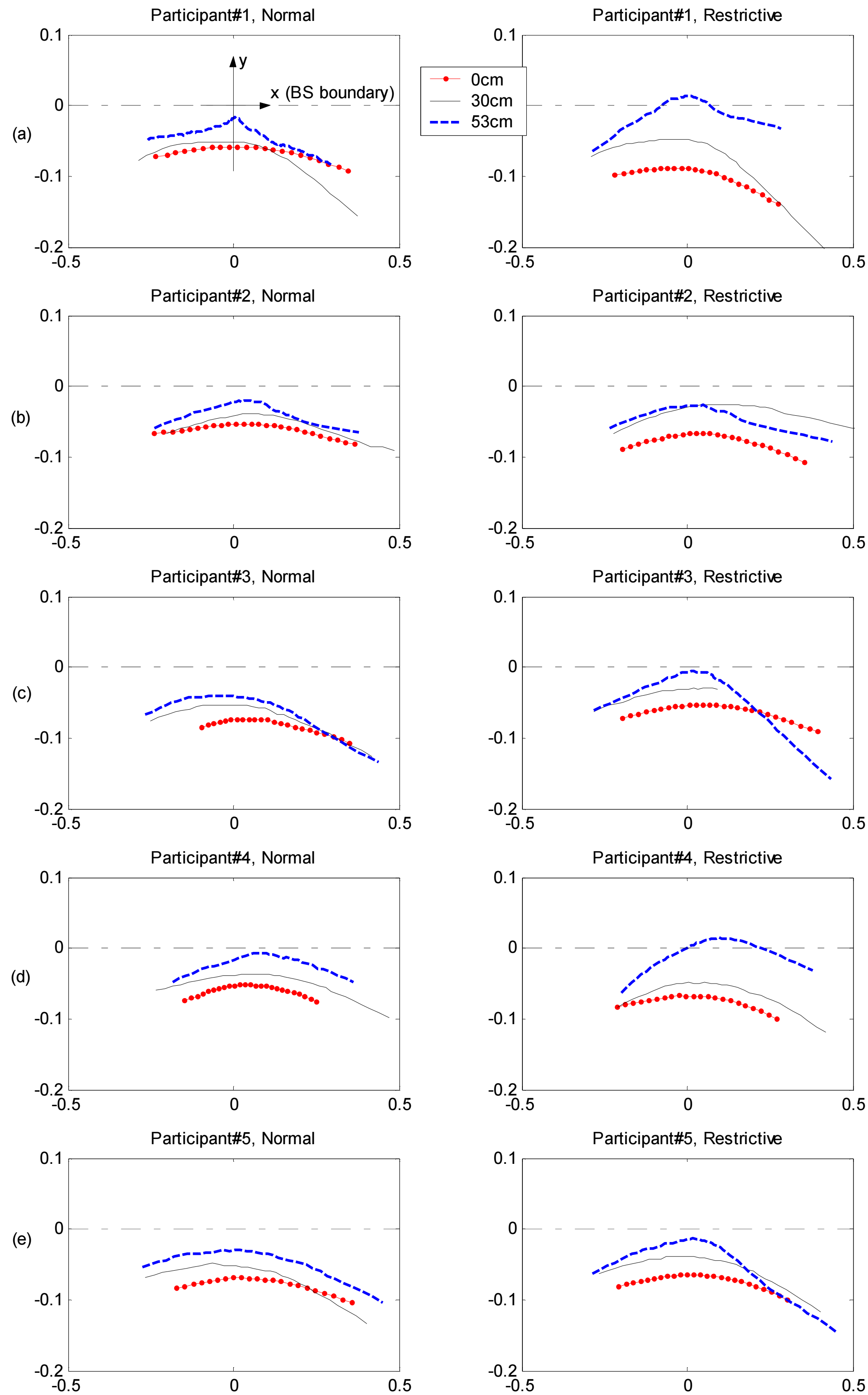


Figure 9 Trajectory of PCOM with different obstacle heights (0, 30 and 53 cm) for different participants (a) –(e). Plots in the left column are for the tests with normal clothing and, plots in the right column are for the tests with restrictive clothing.

Effect on stability parameters

Fig. 9 shows the trajectories of PCOM from toe-off to the heel-landing (heel strike) of right foot when the participant stands on his/her left leg. Therefore, each plot in Fig. 9 corresponds to a top view of Fig. 3. The red dot at the origin of xy-coordinates in Fig. 9 indicates the supporting foot-ball **Z**. The positive axis of y-axis is in the lateral direction. And, the positive axis of x-axis is in progression (forward) direction. As the obstacle height increases, the PCOM trajectory shifts towards the lateral direction, which indicates that the motion gets more unstable laterally. The PCOM of participant #4 even goes outside the lateral boundary when crossing 53cm obstacle. Same is true for the case in restrictive clothing. But, there are some PCOM trajectories that are rather distant from BS boundary even with increase of obstacle height at 53cm obstacle height in restrictive clothing (participant #2, #3, #5). This is because the participant changes his/her crossing strategy from Mode I (crossing in front) to Mode II (crossing sideways) when he/she could not lift up the knee over the obstacle due to the clothing restriction.

DISCUSSION AND CONCLUSION

In this work, the effect of restrictive clothing on functional reach and on balance and gait during obstacle crossing of five normal subjects has been studied using motion capture and stability analysis. The study has shown that restrictive clothing has considerably reduced participants' functional reach and their lateral stability and motion strategy. The study has also shown that restrictive clothing has affected the motion of the participants and forced them to change their motion strategy when crossing higher obstacles. In this regard, the participants rotated their stance foot out (aversion), lifted their arm sideways (abduction), flexed their torso, and increased their hip angle in the medial-lateral (Rolling) and vertical (Yawing) directions. It should be noted that some participants who have shorter legs were incapable of crossing the higher obstacles in the same way they cross lower obstacles. As a consequence, they changed their crossing strategy by using more yawing angles. While this strategy looks safe, the increase in the stance time combined with the rotation of the stance foot may present disaster scenarios especially with slippery or irregular floors.

The stability analysis of a virtual human skeletal model on the other hand has shown that participant's stability has become more critical with restrictive clothing versus normal clothing, and when the participants cross higher obstacles. This behavior is related to the constraint imposed by the restrictive clothing on the relative joint angle limits. This constraint will obstruct the participants from achieving their normal range of angles, which is normally used by the participants to stabilize their motion in different scenarios. The study has also shown that the distance between the PCOM and BS becomes critically smaller with higher obstacles and with restrictive clothing. It should be noted here that in future work, the study would be conducted using a force plate that will provide more information about the unknown floor's reaction forces/moments.

This study has indicated the need for more reasonable number of participants in order to attain more significant results. Besides that, standardized suits should be utilized for specific population and task.

In conclusion, this study has shown that restrictive clothing may impair balance and may put people wearing them at higher risk of slipping and falling.

ACKNOWLEDGMENTS

This research is funded by the US Army TACOM project: Digital Humans and Virtual Reality for Future Combat Systems (FCS) (Contract No.: DAAE07-03-Q-BAA1).

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