Analysis of the integrated use of a motion capture system with a digital human modeling and simulation software for incorporation of future activity

Análise do uso integrado de um sistema de captura de movimentos com um software de modelagem e simulação humana para incorporação da perspectiva da atividade

William Rodrigues dos Santos[1]
Daniel Braatz[1]
Luiz Antonio Tonin[1]
Nilton Luiz Menegon[1]

Abstract: This study presents an analysis of a technical system consisting of the integration of a motion capture system with a human modeling and simulation software aiming to propose ways to use it in the design processes contextualized by ergonomics. Different configurations of the main stages of the integration process are analyzed through experimental tests. Four factorial experiments were conducted to test the possible combinations of the different configurations of the system: i) spatial positioning of virtual environments; ii) drift mitigation; iii) kinematics of the digital human model; and iv) anthropometric compatibility. The results obtained demonstrate how to configure the integrated system towards the positioning of the virtual environment, enabling position correction. Procedures relating the possible interactions between the motion capture body and the work environment with the activity characteristics and the simulation goals were developed. In addition, an iterative systematics was created to match the anthropometry among the real human individual, the human model of the motion capture system, and the digital human model of the simulation software. The operating procedures proposed show the different ways to use the integrated system and the ways to reduce and overcome the limitations and problems arising from the use of digital human models integrated with motion capture systems. Finding ways to use these technologies represents an improvement of the commonly used simulation techniques, contributing to the insertion of future work activity into the design of new productive situations.

Keywords: Ergonomics; Virtual environment modeling; Digital human models; Motion capture systems.

Resumo: *Este artigo apresenta uma análise de um sistema técnico, formado pela integração de um sistema de captura de movimentos com um software de modelagem e simulação humana, visando estabelecer formas de utilização no processo de projetos contextualizados pela ergonomia. Foram analisadas diferentes configurações das principais etapas do processo de integração através de ensaios experimentais e definidos quatro ensaios com delineamento fatorial para testar a combinação das diferentes configurações possíveis do sistema: i) posicionamento espacial de ambientes virtuais; ii) mitigação de erros (drift); iii) cinemática do manequim digital; e iv) compatibilidade antropométrica. Os resultados orientam como configurar um sistema integrado para posicionar o ambiente virtual, permitindo a correção do posicionamento. Também foram criados procedimentos que relacionam as interações possíveis entre o corpo de captura e o ambiente de trabalho com as características da atividade e os objetivos da simulação. Além disso, foi elaborada uma sistemática iterativa para compatibilizar a antropometria entre o ser humano real, o modelo humano do sistema de captura e o manequim digital do software de simulação humana. Os procedimentos operacionais elaborados mostram diferentes possibilidades de uso, formas de reduzir e equacionar as limitações e problemas de utilização de manequins digitais integrados com sistemas de captura de movimentos. O desenvolvimento de formas de uso dessas tecnologias representa uma melhoria das técnicas utilizadas para construção de simulações, contribuindo para inserção da perspectiva da atividade futura no projeto de novas situações produtivas.*

Palavras-chave: *Ergonomia; Modelagem de ambientes virtuais; Manequins digitais; Sistemas de captura de movimentos.*

[1] SimuCAD, Laboratório de Ergonomia, Simulação e Projeto de Situações Produtivas – PSPLab, Departamento de Engenharia de Produção, Universidade Federal de São Carlos – UFSCar, Rod. Washington Luís, Km 235, SP-310, CEP 13565-905, São Carlos, SP, Brazil, e-mail: wsantos@dep.ufscar.br; braatz@dep.ufscar.br; tonin@dep.ufscar.br; menegon@dep.ufscar.br

1 Introduction

Ergonomics concerns the development of knowledge providing support for the analysis and design of products and productive situations. From the perspective of situated ergonomics taking the activity into account means that the general functions, such as postures and movements, are not considered isolatedly, but rather together with behaviors and gestures as they normally occur in design process.

Accordingly, Daniellou (2007) proposes the analysis of reference situations and simulation of a future activity for effective integration of ergonomics into the design process. Human simulation can be extrapolated as a useful tool to expand the interaction space between different actors in the design process, aiming at social construction.

The social construction process seeks, among other things, to consider the work activity as the main factor in the confrontation of different views among the actors (ergonomists, designers, operators, managers, and directors) based on the use of knowledge and questions arising from existing situations that may have similarities with the situation being simulated and are used in the design process (reference situations).

The design also includes another aspect, the technical construction, which in terms of ergonomics, includes the search for tools and operational solutions to perform simulations of the reference situations identified and analyzed. The results of such simulation are predictions for future work.

Therefore, human simulation was introduced in the industry as a tool to facilitate design processes, accelerating their development and cost efficiency (Lämkull et al., 2009). Several authors consider this tool as a way to integrate and analyze the possible ergonomic aspects present in future work activity in the early stages of design (Braatz et al., 2012; Kang et al., 2012; Magistris et al., 2013).

The main feature of human simulation is being able is the positioning of digital human models in operators' real working positions or postures (Ziolek & Kruithof, 2000). Usually, the working posture set in the simulation is a representation of the future work that the software user has, but it does not illustrate the complexity of the future activity (Braatz et al., 2012; Zülch, 2012). Another challenge of using the traditional human simulation is the operational difficulty in positioning the digital human models (mannequins) manually, with the use of the "mouse and keyboard" (Sundin & Örtengren, 2006; Menegon et al., 2011).

Motion Capture Systems (MoCap) can be used to help overcoming the traditional human simulation problems. They enable to capture and record real human movements and edit and animate them with computational tools using digital models.

The use of these systems still poses a number of challenges, particularly in uncontrolled situations, such as production environments. Operations and work environment conditions, such as light, temperature, heat, and materials, can affect the motion capture data accuracy.

Thus, this study analyzes the technical integration process of a motion capture (MoCap) system with modeling tools and digital human simulation. Factorial experiments were carried out with the different configurations of the integration of these technologies to create virtual scenarios that allow incorporating aspects of the future activity into the design of work situations.

2 Human modeling and simulation in ergonomics

Virtual environments of human simulation are defined by the relationship among the scenario, the digital human model, and the analyses (Ziolek & Kruithof, 2000), as shown in Figure 1.

The virtual environment represents the productive situation in design process in terms of materials, equipment, and processes. It is built using CAD (Computer Aided Design) systems based on the definition of engineering aspects that establish the requirements and dimensions of the productive situation.

The digital human model is modeled representing human operators performing a task, based on their anthropometric and biomechanical data. The analyses represent the interactions of the digital human model with the virtual environment where the human model is positioned in the workplace and its postures are modeled. The ergonomic aspects of the design variables (anthropometry, access conditions, space, reach zones and envelopes, visual field, etc.) can then be evaluated. Quantitative assessments can also be carried out using protocols such as RULA, NIOSH, OWAS, and Snook and Ciriello among others.

Human modeling and simulation process can be classified as either static or dynamic. Static simulations are developed with the scenario and the digital human model at a particular pose and specific points in time. Only the scenarios and postures that are considered important for future work are modeled, discretizing and simplifying the course of action. Dynamic simulation seeks to represent the movements of the operator during the performance of a task, allowing understanding the action performance in terms of the scenario, positions, and interactions. There is also, to a lesser extent, discretization and simplification, which are reduced due to the interpolation between interactions.

Both ways of simulating future work can be carried out manually ("mouse and keyboard") or using MoCap systems. In general, the simulations carried out manually require greater operational effort and can
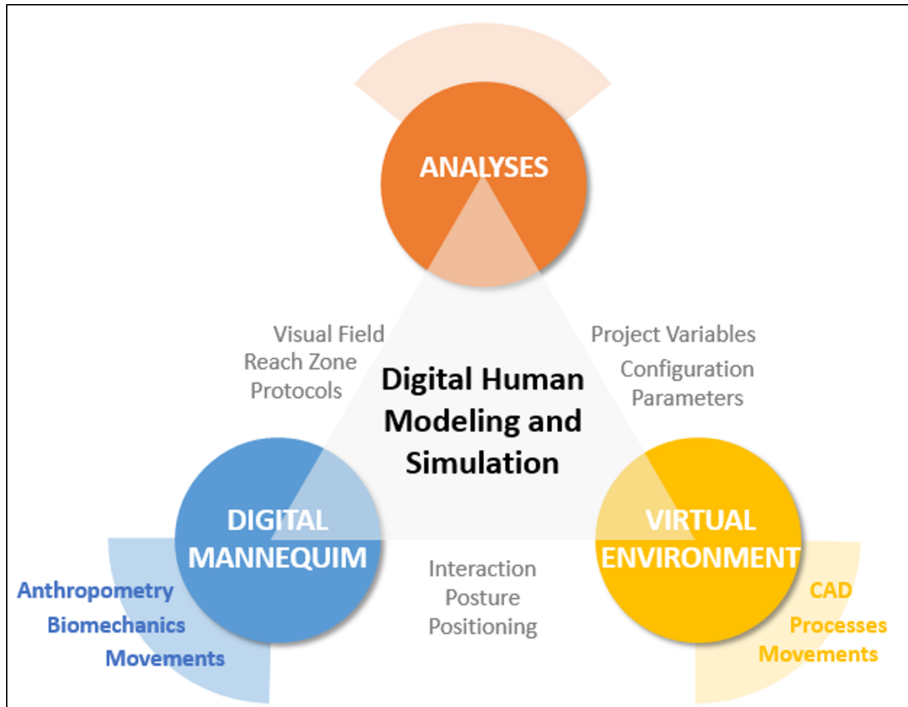
Figure 1. Simulation Process. Source: Adapted from Ziolek & Kruithof (2000).

lead to a simplified representation of the productive situation in design The use of motion capture helps the creation of a less simplified representation or more realistic simulations, i.e. more similar to the future work activity. Figure 2 illustrates motion capture in a real environment and the integration with MoCap and with Digital Human Model (DHM) in a virtual environment.

3 Motion capture systems

MoCap systems can be classified according to the technology used in the design of their sensors (Silva, 1997): electromechanical, magnetic, optical, markerless, and inertial motion capture systems. Each type of sensor determines the requirements and restrictions of the environment in which the motion capture session will be carried out, thus defining the motion capture process and the calibration needs. Investigating these five technologies, Santos et al. (2014) analyzed the freedom of movement during data capture, environment flexibility, and integration with three modeling and human simulation tools. They found that all systems analyzed showed limitations in terms of the established criteria, and inertial technology was the one that best satisfied all criteria. Therefore, inertial technology has been considered as an object of study.

These sensors are composed of accelerometers and gyroscopes. Accelerometers are used to determine

the acceleration and position of the object captured in relation to a relative reference point; the Earth is commonly to use as a reference. Gyroscopes are used to define the angular orientation of objects (Carvalho, 2011). These devices are essential for the determination of the spatial position in the virtual environment and for moving the digital human model (kinematics).

Inertial sensors are subject to errors (drift), which affects the motion capture data quality. These errors include scale factor inaccuracies, misalignment, and noise, which increase during the motion capture sessions and are intrinsic to the process (Carvalho, 2011). More recent inertial sensor models also include magnetometers to reduce this type of error. However, other problems may arise; these problems are related to the presence of metal objects in the environment causing local magnetic field disturbances and leading to errors in the estimated orientation (Roetenberg, 2006). In order to overcome these problems, Roetenberg (2006) proposes the use of a mathematical algorithm, the Kalman filter, which fuses the gyroscope, accelerometer, and magnetometer signals to mitigate these errors.

Another way to reduce motion capture errors is by resetting the velocity of the accelerometer to zero at certain times during the motion capture session (zero-velocity update technique) (Young, 2010). Therefore, it is necessary to know when the object being captured is in contact with an element in the

real environment such as a wall, stairs, floor, and furniture (Contact Point method).

Figure 3 illustrates a typical reason for applying the Contact Point method proposed by Young (2010) during human movement. The gray human model (dotted line) represents the position of the legs obtained by the inertial sensor, and the black human model (solid line) represents the actual position of the legs. At the beginning of the movement (transition from A to B), the inertial sensors accumulate errors
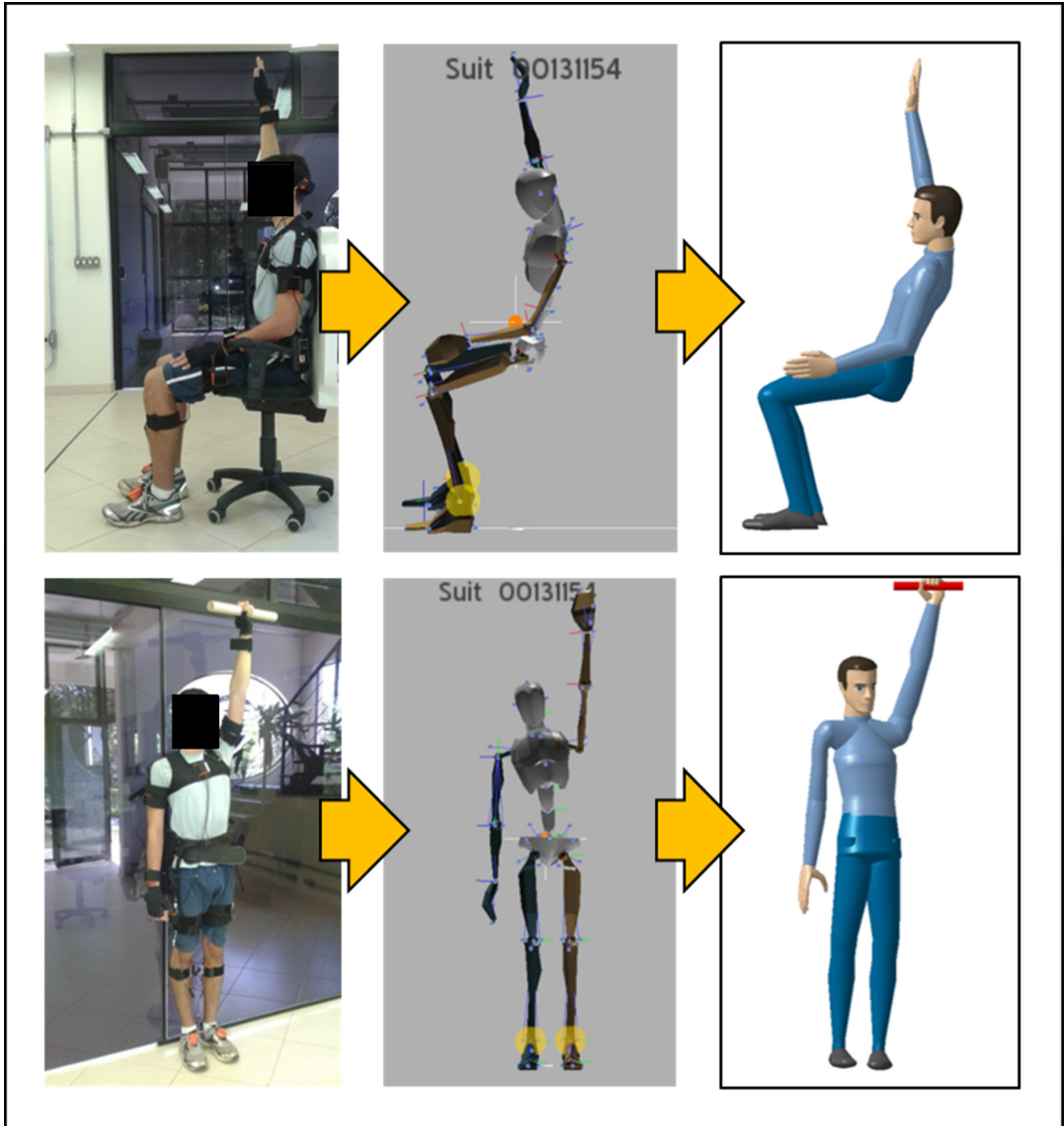

Figure 2. Motion capture in a real environment using Moven and Human Builder.
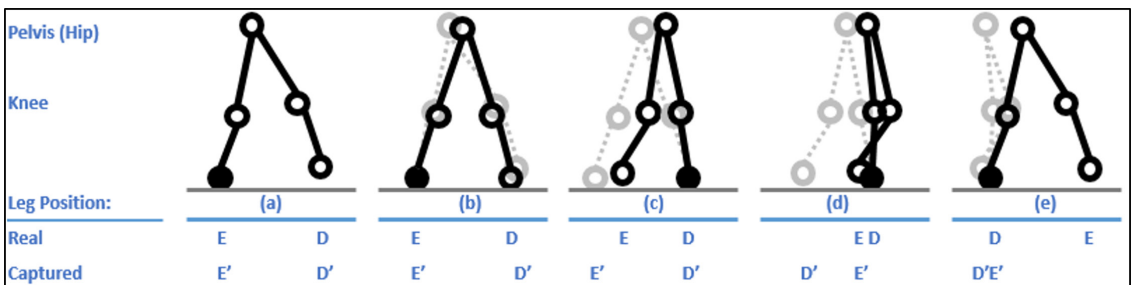

Figure 3. Example of errors generated and accumulated during motion capture. Source: Adapted from Young (2010).

causing drift from real the position of the human model. This Figure shows the effect of the accumulated error during the whole movement (C, D, and E). The Point of Contact Method considers the foot-to-ground contact information to adjust motion capture and mitigate the drift.

Finally, another challenge regards the anthropometric compatibility between the captured object (real human model) and the digital human models used in the MoCap software application and in the human simulation software. Each one of these human models have different anthropometric and biomechanical measures. To understand the effects of the problems involved and reduce the limitations discussed, the experimental tests described below were carried out.

4 Methodological aspects

This is an experimental study of interference effects as it aims to establish cause and effect relationships between independent and dependent variables (Baptista & Campos, 2010). The independent variables are the existing configurations of the process of integration of the technologies, and the dependent variables are the results of different combinations of the configuration that lead to the problems and limitations of this system.

4.1 Integrated system characterization

The experimental tests were carried out using an integrated system with two different computational technologies: (i) Moven MoCap suit, which uses inertial sensors and (ii) the CAD Delmia software, which has a module of digital human modeling and simulation, the Human Builder.

The RTI plugin is used to enable the incorporation of motion captured using the Moven into the human digital model of the Human Builder. The system was initially studied in order to understand the integration process and the configuration possibilities. The three computer technologies (including the RTI) allow the determination of the parameters that influence the outcomes.

There are five steps to set up the Moven that must be followed before the recording of captured movements. **Step 1**: attachment of inertial sensors, data processing device, and cables to the real human model.

Step 2: definition of the scenario, which influences the kinematics of the digital human model movements; the possibilities consider variables related to the environment floor and the human model pelvis.

Step 3: refers to defining of the configuration modes of the magnetometers during movement capture to reduce the effects of drift. There are three configuration modes: i) "Kinematic Coupling Algorithm (KiC)" mode, which ignores the data of the magnetometers in the sensors attached to the lower limbs when the real human model is moving and considers the magnetometer data when the real human model is at rest; ii) "KiC without magnetometers" mode, i.e., the magnetometers are turned off during the entire period of movement capture; and iii) "XKF-3" mode, which uses the magnetometers and the Kalman filter.

Stage 4: the anthropometric measurements of the digital human model of the software application of the Moven system (avatar) are defined. According to Badler (1997, p. 6), an avatar is defined as a "[...] virtual human controlled by a live participant." In the context of the present study, the avatar is the human model of the Motion Capture system software, whose movements are controlled by the real human model (live participant).

Step 5: refers to the calibration of the avatar in relation to the real human model. The purpose of calibration is to align the coordinate system of the inertial sensors to the body segments of the real human model and determine the relative distance between the joints of both biomechanical models (Roetenberg et al., 2013). During this step, the motion capture scenario is also calibrated; it influences the avatar movement direction. When all five steps are performed, motion capture can be then recorded.

The other technology that is integrated into the method is the CAD Delmia software, which requires the creation of the DHM and the customization of its anthropometric measurements.

The last configuration step refers to determining the point of origin of data capture using Moven in relation to the point of origin of these data in the Delmia virtual scenario. There are two possibilities: the first one is to use the Human Builder mannequin as the basis to receive the data recorded, and the second is to use the "magic carpet", which enables moving the point of origin of the motion capture data to a specific point in the "carpet".

4.2 Experimental design

The integration proposed enabled different configurations (possible combinations) of the technical system elements. Therefore, four experimental tests were carried out with the parameterizations in the different stages of the integration process and the problems found during the study. These experiments are presented in Chart 1.

The experimental tests were carried out in a university research laboratory. The building, which has a ground floor and an upper floor, was modeled on Delmia to build the virtual environment. Different preparation procedures and data collection and analysis methods were defined for each test.

Chart 1. Independent variables used in each experimental test.

Experimental Test	Problem found	Variables		
		Moven	**RTI**	**Human Builder (Delmia)**
1) Object positioning in a virtual environment	Lack of absolute coordinate system	V1A) Without scenario calibration	V1C) Default configuration	
		V1B) With scenario calibration	V1D) Mannequin-based configuration	
			V1E) "Magic carpet" configuration	
2) Drift mitigation	Motion capture errors	V2A) KiC mode		
		V2B) "KiC without magnetometers" mode		
		V2C) XKF3 mode		
		V2D) Processing of recorded motion capture data		
		V2E) Sensor reset		
3) Kinematics of the digital human model - Human Builder	Lack of absolute coordinate system	V3A) Default scenario		
		V3B) Flexible floor scenario		
		V3C) Pelvis Fixed scenario		
		V3D) Rigid Pelvis Fixed scenario		
		V3E) Multiple level scenario		
4) Anthropometric compatibility	Difference between the anthropometric and biomechanical models	V4A) Automatic anthropometric model scenario		V4C) Simplified Human
				V4D) Intermediate Human
		V4B) Detailed anthropometric model		V4E) Detailed Human

4.2.1 Experimental Test 1: Spatial positioning of the virtual environment

The laboratory floor was analyzed to find a point where there were no magnetic field disturbances that could affect the calibration process. Thus, the sensors were adequately placed for the initial exploration of the ground floor. The point found was defined as the location to carry out the calibration, establishing the origin and the coordinate system in the Moven software application.

This point was marked on the floor and a coordinate axis (x, y) was defined as the reference for the movement of the real human model. This coordinate system was denominated Real Coordinate System (R).

This same point was modeled in the virtual environment by measuring the distances from the back and side walls of the building. Two lines were modeled passing through the coordinate axes, defining the Virtual Coordinate System (V).

After these preparation procedures, two sessions of data capture were carried out to analyze the results without scenario calibration (V1A) and with scenario calibration (V1B). These sessions of data capture consisted of the linear movement of the real human model across the R system drawn on the floor until reaching the reference points with the right foot.

These two sessions of data capture were integrated with Delmia separately, varying the positioning/origin data: default configuration (V1C), Mannequin-based configuration (V1D), and magic carpet configuration (V1E).

The results were analyzed comparing the origin, direction, and orientation of the real human model movement in the three coordinate systems (Moven system, R system, and V system system). In order to eliminate the drift effects over time, for each set of variables, the sensors were reset and the previously recorded calibration was reused.

4.2.2 Experimental Test 2: Drift mitigation

Based on the definition of the procedures for the spatial positioning of the virtual environment, the effect of the configurations associated with the MoCap system errors were analyzed. The experimental procedure of this test consisted of the following steps:

- Carrying out of sessions of data capture with each of the three magnetometer modes (V2A, V2B, and V2C). The movements in each configuration involved: determining a predefined trajectory and some actions, such as sitting in a chair, jumping over a box, and walking between obstacles. Each trajectory started and stopped in the origin of the coordinate system, completing 1 lap (full circuit). Seven laps ranging from 1.2 to 1.5 minutes were completed with each configuration, and the total time of the motion capture recording was approximately 10 minutes;

- Processing of the recorded motion capture data (v2d) applying the technique proposed by Young (2010). For each magnetometer configuration, the position of the digital human model was corrected at the time each lap was completed, i.e., when the real human model was positioned in the origin of the R system;

- Repetition of the experiment test by resetting the sensors at every lap (V2E) when the real human model was positioned in the origin of the R system.

The results were obtained by measuring the deviations of the real human model position in relation to DHM position. On every lap completed by the real human model, the position of the Human Builder mannequin in the virtual environment was recorded. Drift error was established as the distance between the point that defines the origin of the V system and the reference point of the DHM on every lap.

Data were analyzed by calculating the total error accumulated in the 7 laps for each magnetometer configuration, with the processing of the motion capture data recorded and sensor resetting.

4.2.3 Experimental Test 3: Kinematic of the digital human model

The effects of the scenario configurations: default (V3A), Flexible floor (V3B), Pelvis fixed (V3C), Rigid pelvis fixed (V3D), and Multiple level (V3E) on the kinematics of the digital human model of the Human Builder. The procedures for this test were defined as follows:

- Preparation of the physical and virtual environment: an apparatus was built orthogonal to the x and y axes in the origin of the R system. This apparatus was modeled on Delmia and positioned in the V system origin; it was denominated as the reference lines of the real environment movements with the virtual environment;

- Definition of standard movements: characteristic movements to be made by the real human model during motion capture sessions were defined: movements made while standing (walking), sitting (moving the legs), and in stairs (going up and down stairs). These characteristic movements were used in all scenario configurations;

- Obtaining motion capture data: data of the real human model making the standard movements defined for each scenario configuration were recorded (total of 15 data files);

- Virtual environment analysis: integration of the motion capture sessions performed with the virtual Human Builder mannequin in the modeled virtual environment.

The results were analyzed comparing, for each scenario configuration, the movements of the real human model with those of the digital human model created by the Human Builder in the virtual environment in relation to the reference lines of the movement.

4.2.4 Experimental Test 4: Anthropometric compatibility

This test evaluated the effect of the anthropometric models of the Moven and Human Builder to ensure compatibility of the anthropometric measurements of the real human model with those of the digital human model created by the Human Builder. To make the comparison between these anthropometric models, a protocol containing the functional dimensions of the body proposed by Panero & Zelnik (2002) was developed. These dimensions are typical working postures involving the upper and lower limbs functional reach dimensions.

The Moven has two anthropometric models. The first model is called "simplified" (V4A) and has only 2 anthropometric measurements: height and foot

size. The other body dimensions are automatically generated. The second model, called "detailed" (V4B), has 8 anthropometric measurements: body height, foot size, arm span, hip height (ground to most lateral bony prominence of greater trochanter), knee height (ground to lateral epicondyle on the femoral bone), malleolus height (ground to distal tip of lateral malleolus), hip width, and shoulder width; the thickness of the real human model's shoe sole is also a required measurement.

The Anthropometric model of the Human Builder enables customization of up to 103 anthropometric measurements. However, there is a match between these measurements with only 6 Moven measurements: body height, foot size, arm span, hip height, knee height, and malleolus height.

Because there are major differences between the anthropometric models of the Moven and the Human Builder, three anthropometric levels of customization were established for the Human Builder. In the first customization level, called "Simplified Human" (V4C), 2 anthropometric measurements were customized (the same measurements of the simplified model of the Moven system). In the second customization level, called "Intermediate Human" (V4D), 6 anthropometric measurements, which are also included in the Human Builder and match the measurements of the anthropometric detailed model of the Moven, were customized. Finally, in the last customization level, the "Detailed Human" (V4E) was created, in which 6 measurements match those of the anthropometric detailed model of the Moven. It includes 5 other steps: acromion height (sitting), buttock-heel length (sitting), forearm-hand length (sitting), arm reach from wall, and thumb tip reach. These measurements are not directly related to those of the Moven anthropometric models, but they influence the dimensions of the upper and lower limbs of the Human Builder, and therefore can influence the functional dimensions of the body measurements of the defined protocol.

In addition, preliminary tests showed that it would not be possible to use the same numerical value for the corresponding anthropometric measurements due to the differences in the logical architecture used in the construction of the biomechanical models of the Moven and the Human Builder.

The anthropometric measurements of the Moven models were obtained according to the software users' guide (Xsens, 2012), using Qualysis, an optical MoCap System (Qualisys Motion Capture System), and the Visual3D software. The anthropometric measurements of the Human Builder models were obtained using a tape measure.

As the Moven system does not provide hand movement measurements and the protocol has postures or positions that require grip strength,

the real human model held a piece of plastic tube (1.5 inches in diameter) to simulate this effect. At the same time, this tube was modeled using CAD Delmia and positioned so that the DHM would also hold it. After these preparation procedures, data were collected:

- Creation of the Moven anthropometric models: Simplified (V4A) and detailed (V4B) models;

- Motion capture: two data capture sessions were carried out using the anthropometric models (one using the simplified model and the other using detailed model) and the protocol containing the functional dimensions of the body;

- Posture generation: data capture sessions were carried out using the Moven system integrated with Delmia and two catalogs containing the protocol positions were produced;

- Creation of DHM using Human Builder: three digital mannequins were created, "Simplified Human" (V4C), "Intermediate Human" (V4D), and "Detailed Human" (V4E).

The results were analyzed quantitatively comparing the differences between the functional dimensions of the body of the real human model with those of the three levels of customization detail of the digital human models of the Human Builder in the virtual environment.

Based on the experimental test results, operating procedures for using the integrated system were proposed.

5 Results and discussion

5.1 Spatial positioning of virtual environments

This experimental test involved the following variables of the motion capture system and the RTI plugin:

- V1A: when the scenario was not calibrated, the movements of the Moven avatar occurred in the coordinate system that uses the Earth as a reference point;

- V1B: when the scenario was calibrated, the movement occurred in the coordinate system created by the MoCap system software application;

- V1C: The default configuration of the RTI plugin generated the motion capture data in the origin of the coordinate system of Delmia desktop;

- V1D: the use of the Mannequin-based configuration generated the motion capture data in the reference

point where the digital model Human Builder was positioned;

- V1E: the use of "magic carpet" enabled placing the motion capture data in the reference point of the carpet modeling.

Thus, in order to enable the spatial positioning of the virtual environment in the same position and direction of a real physical environment, two conditions are required in the V system: (i) its origin has to overlap the origin of the R system; and (ii) the x-axis should have the same direction and orientation of the R system.

The scenario calibration generates the movements of the Moven avatar in a local and defined coordinate system. When this configuration is combined with the use of the mannequin-based configuration, the coordinate system of the Moven becomes compatible with that of the Delmia. However, these configurations require that the environment does not have **ferromagnetic materials** that can disturb the magnetic field, preventing proper calibration. Therefore, the calibration of the Moven and the scenario in these types of environments should be performed in a place without ferromagnetic material interference and then carry out motion data capture in the hostile environment. For an effective integration with Delmia, it is recommended to use **the magic carpet** to shift the origin of Moven data to the desired position by positioning the geometry with its origin according to the directions of the coordinate system used in the data capture. The operating procedures for spatial positioning of virtual environments are presented in Chart 2.

After defining the proper procedures for spatial positioning, it was possible to conduct the drift mitigation experimental test.

5.2 Drift mitigation

In all factorial experiments, the magnetometer configuration modes showed major drift (V2A, V2B, and V2C), as can be seen in Figure 4. In general, the smallest amount of drift was obtained when the

magnetometers were not used (V2B) in the data capture sessions. This configuration mode showed increasing tendency towards drift stability every lap. The KiC mode (V2A) showed less amount of drift in the first two laps, but it displayed tendency towards increase over time. The mode with the Kalman filter, XKF-3 mode, (V2C) showed the largest amount of drift in all laps among the three modes used. It is worth noting that during lap 5, this mode had a drift peak of more than 1.8 meters (1800 cm). This atypical behavior may have been caused by a data transmission problem during the data capture session. Therefore, the results obtained in this lap were excluded for the three modes to allow comparative analysis.

It was possible to reduce the drift during data capture by resetting the velocity of the accelerometer to zero, as proposed by Young (2010), but it was not possible to eliminate it completely. The drift was reduced with the treatment of the data captured (V2D) in all modes of configuration of the magnetometers. Considering the error accumulated during the six laps, the three modes of magnetometer configuration, KiC, KiC without magnetometers, and XKF3, showed improvement of 28%, 52%, and 67%, respectively, as illustrated in Figure 5.

The drift values after resetting of the sensors (V2E) at every lap, for all modes of the magnetometers, were similar to those obtained after data processing. However, during this procedure, the coordinate
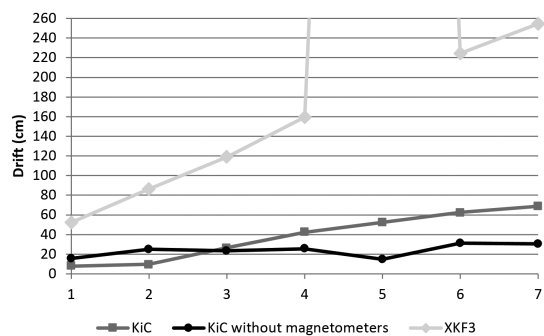

Figure 4. Drift behavior of the three configuration modes of the magnetometers.

Chart 2. Operating procedures for spatial positioning of virtual environments.

Is there a physical environment without magnetic field disturbances?	Yes	• perform calibration of the *avatar* in the place of data capture (Moven Studio); • perform scenario calibration (Moven Studio); • set the position of the human model in the origin of the coordinated system created (Delmia); • use mannequin-based configuration (RTI);
	No	• perform calibration of the avatar in a place without magnetic field disturbances (Moven Studio); • perform scenario calibration (Moven Studio); • use the magic carpet (RTI); • set the position of the magic carpet in the origin of the virtual coordinated system (Delmia);

system of the Moven software application was also reset, and therefore the avatar lost the reference of its own coordinate system, preventing the capture of movements in the course action of the operator.

It was observed that the best results in terms drift reduction were obtained when the magnetometers were turned off during the entire period of movement capture. In addition, all magnetometer configuration modes showed drift reduction with data treatment. However, it is important to mention that in order to carry out data processing, it is necessary to know all real human model coordinates (x, y, z), which must be added to the motion capture software application for position correction. This procedure is only possible with the spatial positioning of the virtual environment, as carried out in the Experimental Test 1.

With the blueprint of the research laboratory (where the experimental tests were carried out) created in CAD environment, it was possible to know the coordinates (x, y, z) of the real human model in the real environment. Therefore, the procedures for mitigation of drift associated with the configuration of the magnetometers and the positioning of virtual environments are described below:

- Use the mode with the magnetometers turned off (Moven);
- Create a virtual environment positioned relative to the real environment (Experimental test 1);
- Determine points (x, y, z) for position correction;
- Process the captured data using the points determined for position correction (Moven).
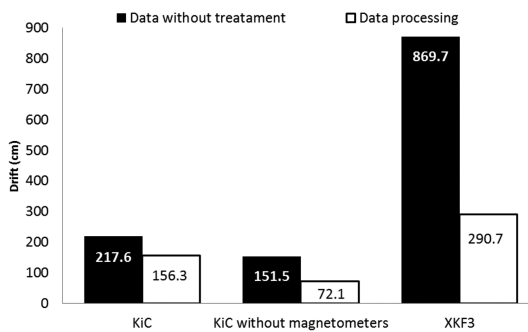

Figure 5. Drift improvement after correction of avatar positioning.

5.3 Kinematics of the digital human model

The results of the experimental test of the kinematics of the digital human model showed that in each chosen scenario there was a reference point that remained fixed in the avatar of the Moven software application during the entire period of movement capture. This same point remained fixed in the digital human model of Human Builder when the motion capture was integrated with Delmia. Comparing the different types of scenarios with the types of movements performed in this experimental test, the fixed reference point of the Moven avatar of each type of scenario and the effects on the movements of the digital human model of the Human Builder were determined, as shown in Chart 3.

Thus, the choice of an appropriate scenario depends on the characteristics of the work activity and the simulation goals. In order to determine the relationship between the characteristics of the work activity and the simulation goals, four types of interactions were created:

i) interactions in the horizontal plane only: walk, lift objects, use tools, carry load;

ii) interactions in the sitting position only: sitting job tasks such as operate machines, drive;

iii) interactions in the horizontal and vertical plane: climb stairs, scaffolding, platforms, and others;

iv) mixed interactions: composed of working in a sitting position and horizontal and/or vertical movements.

For each type of desired interaction, an operating procedure was proposed, as shown in Chart 4.

5.4 Anthropometric compatibility

The results of the experimental tests of anthropometric compatibility showed that despite the differences in the logical architecture used in the construction of the anthropometric models of the Moven and Human Builder, it is possible to establish an anthropometric match between the human models of the integrated system with a certain margin of error.

Table1 shows the percentage deviations between the values of the functional dimensions of the body

Chart 3. Kinematics of the Moven *avatar* for each type of virtual scenario.

Type of scenarios	Kinematics
Default (V3A)	Movements are generated using the right foot as reference (fixed), allowing movements in the horizontal axis.
Flexible floor (V3B)	
Pelvis fixed (V3C)	Movements are generated with the hips fixed, preventing movements in the horizontal axis.
Rigid pelvis fixed (V3D)	
Multiple level (V3E)	Movements are generated using the right foot as reference, with freedom of movement in the horizontal and vertical axis.

Chart 4. Operating procedures for scenario selection based on the type of interaction desired.

Interactions in the horizontal plane only	• Chose the default scenario (Moven Studio); • Define distance from the floor and ceiling as the reference point of the Human Builder (Delmia).
Interactions in the sitting position only	• Chose pelvis fixed scenario (Moven Studio); • Define "H point" as the reference point of the Human Builder (Delmia); • Measure the distance between the virtual floor and the "H point" (Delmia).
Interactions in more than one plane	• Chose the multiple level scenario (Moven Studio); • Define distance from the floor and ceiling as the reference point of the Human Builder (Delmia); • Determine the points of contact with the ground (Moven Studio).
Mixed interactions	• Divide data capture according to the desired interaction (Moven Studio); • Use the procedures specific to the type of interaction chosen.

Table 1. Measurements (cm) and percentage deviations obtained in the anthropometric compatibility experimental test.

Functional dimensions of the body	Real human model measurements	Simplified Moven and Simplified Human	Simplified Moven and intermediate Human Builder	Simplified Moven and detailed Human	Detailed Moven and Simplified Human	Detailed Moven intermediate Human	Detailed Moven and Detailed Human
Thumb tip reach extended	103.0	96.0	103.0	92.0	107.0	103.0	100.0
		6.8%	0.0%	10.7%	3.9%	0.0%	2.9%
Buttock-heel length	125.0	124.8	128.0	122.8	125.0	130.0	128.0
		0.2%	2.4%	1.8%	0.0%	4.0%	2.4%
Vertical reach (height sitting)	138.0	145.0	142.0	139.0	145.0	142.0	137.0
		5.1%	2.9%	0.7%	5.1%	2.9%	0.7%
Thumb tip reach	84.0	93.0	90.0	86.0	93.0	90.0	86.0
		10.7%	7.1%	2.4%	10.7%	7.1%	2.4%
Side arm reach	96.5	95.0	97.0	92.0	94.0	94.0	95.0
		1.6%	0.5%	4.7%	2.6%	2.6%	1.6%
Vertical grip reach	226.0	222.0	222.0	222.0	225.0	223.0	223.0
		1.8%	1.8%	1.8%	0.4%	1.3%	1.3%

(protocol) obtained for the real human model and the values obtained in the Moven and Human Builder virtual environment. It can be observed that the lowest deviations were obtained with the detailing of the DHM, reaching a deviation value of 11.3% in relation to 6 different postures. However, the high relative standard deviation indicates random behavior of the process of difficult modeling anthropometric compatibility.

The importance of the anthropometric compatibility of the system models lies in the application the anthropometric principles, as highlighted by Menegon et al. (2002). These principles establish that the design variables should be defined according to the work activity or functional tasks (upper and lower limb functional reach and other functional tasks such as grasp-transport-release tasks), considering the measurements related to extremes of a population (5th or 95th percentile, depending on the work situation). This will ensure the functional reach for 90% of the population.

Therefore, the results of the anthropometric compatibility experimental test suggest the need for a compatibility iterative process based on the variables

defined for the specific project in which the motion capture technique will be applied. A posture protocol should be developed containing the anthropometric data that are directly related to these variables or that can be independently measured.

The data obtained according to the functional dimensions of the protocol are used as a basis for comparison with the data obtained for the Human Builder mannequin. Thus, we recommend using the Moven detailed anthropometric model with the Human Builder detailed anthropometric model to start the iterative process. If the initial result is not satisfactory, more anthropometric measures should be carried out until obtaining good or adequate results.

The compatibility between the anthropometric models of the integrated system poses a significant challenge for its use in precise and detailed analysis of movements in terms of three aspects. The first aspect involves specifically the Moven motion capture system, which does not provide hand movement measurements, thus making it impossible to obtain precise movements involved in manual activities. The second aspect refers to the difference between the biomechanical and anthropometric models of the

system. The real human model has over 200 joints and a wide range of possibilities of anthropometric measurements. This real model is represented in the Delmia virtual environment by the digital human model of the Human Builder, which has a maximum of 103 anthropometric measurements and 50 articulated segments (joints). The integration of these two models is "intermediated" by the Moven Avatar, which has a maximum of 9 anthropometric measurements and 22 joints. Additionally, the degrees of freedom of computational biomechanical models should be considered. Although the Human Builer does not have an articulated model, the movements of each segment try to simulate the human body movements. On the other hand, all joints of the Moven biomechanical model have 3 degrees of freedom, which does not represent the human reality. These facts show a reduction in the complexity of human representation in digital environments, which hinder compatibility between the human digital models of the integrated system. hinder compatibility. Finally, the third aspect is related to the operational difficulty in obtaining the anthropometric measurements that require different techniques and methods (Menegon et al., 2002). Such difficulties were encountered in obtaining the measurements of the virtual anthropometric models (Moven and Human Builder) and the functional body dimensions of the protocol prosed by Panero & Zelnik (2002).

6 Conclusions

In the present study, operating procedures for the integrated use of a motion capture system in virtual scenarios and a CAD software that includes digital human models were proposed. Considering the technical process to create virtual environments for human modeling and simulation, introduced by Ziolek & Kruithof (2000), the integrated system contributes to two relevant aspects: the first one is related to the simultaneous presence of digital models and a CAD system, in which the environments (geometries) are modeled and can be edited in the same environment. This fact facilitates the creation of human simulation since, unlike other simulators available on the market, import or export of geometries can be dispensed with. The second aspect is related to the creation of interactions (analyses). The use of an integrated system allows capturing real movements of workers or users and set their position in the virtual environment in relation to the actual place of work or use, contributing to reduce the time to conduct this type of analysis and to correct positioning errors associated with the "mouse and keyboard" method.

In addition to the technical aspects, the integrated use of these systems can also contribute to the social process (Daniellou, 2007) that is characterized by opportunities to discuss and build consensus about the

different object-world of social actors. The simulation scenarios created by ergonomists seek to represent the proposal of future work situation, which should be formulated, discussed, and validated together with the project participants. Human simulations created using motion capture systems have the advantage of enabling more realistic and contextualized movements than those of traditional techniques. Moreover, the integration with the CAD system enables a better understanding of the motion capture inherent errors and limitations, contributing to the use of scenarios (composed of the environment, models, and their interactions) as intermediary objects in the design processes. Traditionally, intermediary objects refer to schematic representations in CAD drawings, typical of the designers' rationality and which can limit the participation of other actors that are not used to this "language". The integration of CAD with digital human models and motion capture support enables better incorporation of a future work activity (according to the concept of situated ergonomics and can contribute to the understanding and exchange of knowledge between the actors, helping the creation of effective and safe productive situations in terms of production and health.

References

Badler, N. (1997). *Virtual humans for animation, ergonomics, and simulation*. Philadelphia: University of Pennsylvania.

Baptista, M. N., & Campos, D. C. (2010). *Metodologia de pesquisa em ciências: análises quantitativa e qualitativa*. 2. ed. Rio de Janeiro: LTC.

Braatz, D., Menegon, N. L., Fontes, A. R. M., & Tonin, L. A. (2012). Simulação humana digital na concepção de postos de trabalho: estudo comparativo de casos. *Gestão & Produção*, 19(1), 79-92. http://dx.doi.org/10.1590/S0104-530X2012000100006.

Carvalho, A. G. (2011). *Influência da modelagem dos componentes de bias instabilidade dos sensores inerciais no desempenho do navegador integrado SNI/GPS* (Dissertação de mestrado). Instituto Militar de Engenharia, Rio de Janeiro.

Daniellou, F. (2007). A ergonomia na condução de projetos de concepção de sistemas de trabalho. In P. Falzon (Ed.), *Ergonomia* (Cap. 21, pp. 303-315). São Paulo: Blucher.

Kang, B., Lee, D., Chung, M., Kyung, G., & Nam, K. (2012). A method to create dynamic motions of digital human models and a case study. In *Proceedings of the 56th Human Factors and Ergonomics Society* (pp. 2542-2546). Boston: SAGE. http://dx.doi.org/10.1177/1071181312561528.

Lämkull, D., Hanson, L., & Örtengren, R. (2009). A comparative study of digital human modelling simulation results and their outcomes in reality: a case study within manual assembly of automobiles. *International Journal*

of Industrial Ergonomics, 39(2), 428-441. http://dx.doi.org/10.1016/j.ergon.2008.10.005.

Magistris, G., Micaelli, A., Evrard, P., Andriot, C., Savin, J., Gaudez, C., & Marsot, J. (2013). Dynamic control of DHM for ergonomic assessments. *International Journal of Industrial Ergonomics*, 43(2), 170-180. http://dx.doi.org/10.1016/j.ergon.2013.01.003.

Menegon, N. L., Braatz, D., & Tonin, L. (2011). Simulação humana. In F. Másculo & M. Vidal. *Ergonomia: trabalho adequado e eficiente* (pp. 365-393). Rio de Janeiro: Elsevier/ABEPRO.

Menegon, N. L., Braatz, D., Secchin, V. M. S., Regazzini, M. L. L., La Salvia, A. B. N., Pereira, W. A., Naveiro, D. M., Zamberlan, M. C. P. L., & Pastura, F. C. H. (2002). Pesquisa Antropométrica Embraer. In *Anais do 12º ABERGO*. Rio de Janeiro: ABERGO.

Panero, J., & Zelnik, M. (2002). *Dimensionamento humano para espaços interiores: um livro de consulta e referência para projetos*. Barcelona: Gustavo Gili. 320 p.

Roetenberg, D. (2006). *Inertial and magnetic sensing of human motion* (Tese de doutorado). Universidade de Twente, Alemanha, Enschede.

Roetenberg, D., Luinge, H., & Slycke, P. (2013). *Xsens MVN: Full 6DOF Human Motion Tracking Using Miniature Inertial Sensors*. The Netherlands: Xsens.

Santos, W., Tonin, L. A., Brratz, T., Wu, R. L., & Menegon, N. L. (2014). Avaliação de tecnologias de captura de movimentos em projetos de situações produtivas. In *Anais do 17º ABERGO*. Rio de Janeiro: ABERGO.

Silva, F. W. S. (1997). *Motion Capture: introdução à tecnologia*. Rio de Janeiro: Laboratório de Computação Gráfica, COPPE/UFRJ.

Sundin, A., & Örtengren, R. (2006). Digital human modeling for CAE applications. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (pp. 1053-1078). New Jersey: John e Wiley & Sons.

Xsens. (2012). *Moven: user manual. Moven Motion Capture System*. The Netherlands: Xsens Technologies B.V.

Young, A. D. (2010). From posture to motion: the challenge for the real time wireless inertial motion capture. In *Proceedings of the 5th International Conference on Body Area Networks* (pp. 131-137). New York: ACM.

Ziolek, S. A., & Kruithof, P. C. J. (2000). Human modeling & simulation: a primer for practioners. In *Proceedings of the 44th HFES* (pp. 825-827). San Diego: HFES.. http://dx.doi.org/10.1177/154193120004403839.

Zülch, G. (2012). Features and limitations of digital human models: a new German guideline. *Work: A Journal of Prevention, Assessment and Rehabilitation*, 41(Supl 1), 2253-2259. PMid:22317050.