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Real Handball Goalkeeper vs. Virtual Handball Thrower

Abstract

Virtual reality offers new tools for human motion understanding. Several applications have been widely used in teleoperation, military training, driving and flying simulators, and so forth. We propose to test if virtual reality is a valid training tool for the game of handball. We focused on the duel between a handball goalkeeper and a thrower. To this end, we defined a pilot experiment divided into two steps: an experiment with real subjects and another one with virtual throwers. The throwers' motions were captured in order to animate their avatar in a reality center. In this paper, we focused on the evaluation of presence when a goalkeeper is confronting these avatars. To this end, we compared the goalkeeper's gestures in the real and in the virtual experiment to determine if virtual reality engendered the same movements for the same throw. Our results show that gestures did not differ between the real and virtual environment. As a consequence, we can say that the virtual environment offered enough realism to initiate natural gestures. Moreover, as in real games, we observed the goalkeeper's anticipation to allow us to use virtual reality in future work as a way to understand the goalkeeper and thrower interactions. The main originality of this work was to measure presence in a sporting application with new evaluation methods based on motion capture.

1 Introduction

Studying human motor control still remains a challenging task. Indeed, natural motion control is the consequence of many parameters (biomechanical, physiological, psychological, sociological, et cetera). Among all these parameters, only a few of them can be captured. Hence, experiments that consist of measuring only a subset of these parameters may ignore crucial ones. The main problem is to ensure that the conditions are exactly the same between several separated experiments. Without this constraint, no generality about motion control can be deduced, and the large standard deviations are considered as noise whereas it may be due to different experimental conditions.

Let us consider now a handball goalkeeper that tries to stop balls. One of our aims was to identify the elements used by the handball goalkeeper to select a strategy, when he is confronting a thrower. Real experiments raised the question of reproducibility. Indeed, nothing ensures that two throws are exactly identical, even those performed by a unique thrower, who does his or her best to throw exactly the same way. Several external parameters may interfere with the experiments such as a small change in the motion coordination of the thrower, the behavior of the crowd, and the background noise. In conclusion, we cannot link the handball goalkeeper's strategy to a unique situation if we

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cannot eliminate such random phenomena. Virtual reality is a promising tool to overcome these limitations because it makes it possible to ensure reproducibility.

Nevertheless, using virtual reality instead of conducting real experiments raises new questions. First, we have to take presence into account. Presence denotes the subjective feeling of "being there" and was mainly studied through behavioral analyses (Schuemie, Van Der Staaten, Krijn, Van Der Mast, CAPG, 2001). Hence, in our case, did the subject really react as in the real world? To this end, the virtual environment needs to be as close to a real scene as possible. Synthetic buildings, areas, characters, and motions have to be considered. The role of the quality of the geometric model has been pointed out by Hodgins, O'Brien, and Tumblin (1998). Second, in addition to graphical realism, the synthetic characters that inhabit the virtual environment may act as real actors do. Thalmann (1996) categorized four kinds of virtual characters:

- *Avatars* act exactly as the user does.
- *Guided actors* are driven by users via the concept of metaphors.
- *Autonomous agents* have their own behavior. They perceive their environment and can interact with it.
- *Perceptive and interactive agents* are autonomous agents who are aware of other actors and can communicate with them.

Moreover, we also have to consider the interactions that are necessary to make the real subject interact with the virtual world. Several kinds of interactions may occur between these agents. Noser, Pandzic, Capin, Magnenat-Thalmann, and Thalmann (1996) experimented with an interaction between a real tennis player (represented by his avatar) and a virtual one. The virtual player was a perceptive and interactive agent driven by a behavioral model. However, the avatar was as depicted only a part of a human body composed of an arm and a racket. The captured motion of the real tennis player is replayed on this virtual arm without taking any motion details into account. No attention was paid to the effects given to the ball and to the complex player displacements all over the court. Molet et al. (1999) made two real players interact with each other in a shared environment via the VLNET network (Capin, Pandzic, Noser, Magnenat-Thalmann, & Thalmann, 1997). The two players saw their own avatar (only the arm and the racket) playing with a synthetic human-like figure. As in the previous work, the user was not able to play tennis as in the real world. This kind of virtual game cannot be applied directly to study real sporting motions performed by high-level athletes. Other applications were dedicated to evaluating and training sportsmen. For example, virtual reality was used to test a collective sport strategy by immersing a coach in a simulated game (Metoyer & Hodgins, 2000). In this game, a coach gave orders to synthetic players while a behavioral model drove the opponents. Nevertheless, the simulated behavior was again not compared to real situations and the coach did not act as in real games, but used metaphors to drive his team. On the contrary, bobsleigh drivers were asked to train on a simulator for the winter Olympic games (Huffman & Hubbard, 1996). In this study, the simulator was designed to make the drivers behave as in the real world. However, no analysis was performed to verify if the driver really acts as in the real world.

To sum up, previous work on virtual reality was generally based on metaphors to animate avatars and to drive the virtual environment. We propose a set of experiments to verify if the motions performed by a subject immersed in a virtual environment are similar to the ones performed in the real world. Task performance related to the level of presence was previously studied (Slater, Linakis, Usoh, & Kooper, 1996). In this earlier work, behavioral analyses were carried out without accounting for the subject's gestures. In sport, gestures are directly linked to performance, so evaluating the gesture is necessary. We performed a two-step process. First, we captured the motion of a handball thrower and goalkeeper during a real duel. Then we replayed the thrower's motion in a virtual environment, and we verified if the goalkeeper reacted as in the real world by capturing his motion. In the second step, we modeled a synthetic thrower that had to replay the captured motions of real handball throwers. In that sense, it could be viewed as an avatar that acted as a real subject, but not in real time. The synthetic actor was designed to be able to perform other motions (such as those computed by a model), but only the restitution of captured motions was used in this work. The quality of the avatar motion was essential to ensure presence.

To this end, we chose to replay captured motions while accounting for constraints such as ensuring foot contact without sliding, adapting the motion to the synthetic skeleton, and so on. We also wished to modify slightly the original motion to investigate the consequences of each change on the goalkeeper's behavior. As a consequence, we chose to use motion warping and blending techniques. Motion warping was experimented with by modeling the trajectories in the temporal (Witkin & Popovic, 1995) or frequency domain (Unuma, Anjyo, & Takeuchi, 1995). The main drawback of the frequency domain parameterization was the lack of the resulting motion controllability. Indeed, changing the weight of a harmonic is not intuitive and drives us to a trial-and-error repetitive process. Changing control points or adding space-time constraints (Witkin & Kass, 1988) is more intuitive. Captured motions have to be corrected to be used with such a method. For example, noise has to be filtered out and anatomical corrections performed (Molet, Boulic, & Thalmann, 1996; Bodenheimer, Rose, Rosenthal, & Pella, 1997). For our application, procedural animation (Zeltzer, 1982; Boulic, Magnenat-Thalmann, & Thalmann, 1990; Bruderlin & Calvert, 1996) and dynamic simulation (Arnaldi, Dumont, Hégron, Magnenat-Thalmann, Thalmann, 1989; Hodgins, Wooten, Brogan, & O'Brien, 1995; Multon, Nougaret, Hégron, Millet, & Arnaldi, 1999) were not appropriate. Indeed, even for accurate models, the synthetic motions could not be reliably compared to the ones measured in real games.

In Section 2, we describe the methods chosen to animate the virtual thrower. Section 3 gives information about the real and virtual experiments carried out with one handball goalkeeper. Finally, we conclude by asking if such a method may be useful to better understand the duel between the handball goalkeeper and the thrower and give some perspectives.

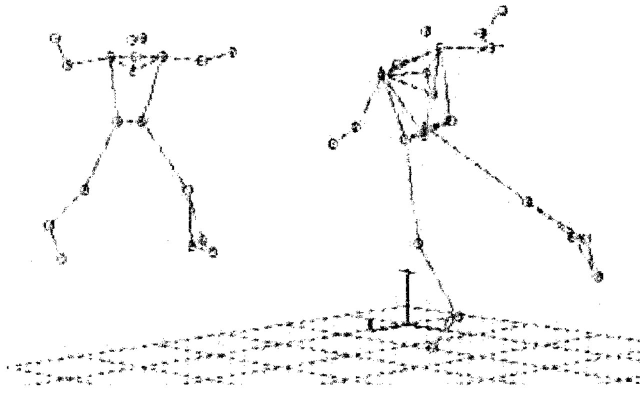

Figure 1. *Handball thrower and goalkeeper.*

2 From Mocap to Virtual Reality

The first part of this study is a preliminary experiment involving a real handball goalkeeper and throwers. Handball is a game confronting two teams of seven players against each other, on a 40 × 20 m field. The aim is to make goals by throwing a ball with the arm at a minimum of 6 m away from a goalkeeper. Hence, a duel between the thrower and the keeper occurs and raises some strategic questions. What kind of information is used by the goalkeeper to intercept the ball?

The aim of this study was to capture the motion of a real handball thrower together with the corresponding goalkeeper's motion. As a consequence, we were able to analyze the goalkeeper's reaction in front of several handball throws: we identified space-time constraints that link the thrower (for each throw) and the goalkeeper's behavior. To this end, we used an optoelectronic motion capture system Vicon370, composed of seven infrared cameras set up at a frequency of 60 Hz. (See Figure 1.)

The cameras were placed to cover a 12 × 6 m field of measurement. To cover this space and to better capture the action of the thrower and the goalkeeper, we placed the cameras along a circle all around the playing area. The subjects were fitted with 26 circular reflective markers to precisely reconstruct the 3D orientation of each segment. (See Figure 2.)

To animate a synthetic skeleton with the resulting

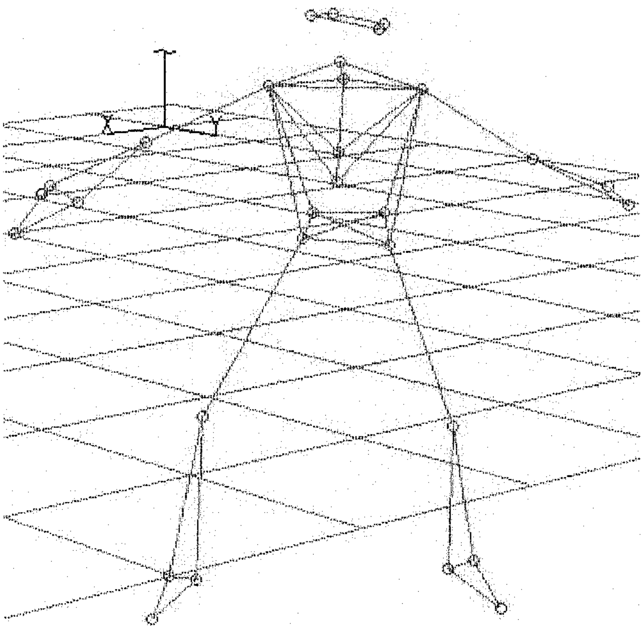

Figure 2. *Location of the reflective markers on the subject.*

trajectories, we performed a set of post-processing. For our study, we used a 29-DOF (including three rotations around the shoulder, one around the elbow, none around the wrist) geometric model. Among other things, optical motion capture systems imply dealing with occlusions (missing points). Hidden markers are not reconstructed, and the resulting 3D trajectories exhibit holes. Of course, before animating a human-like figure, we had to retrieve these missing points. We used a global framework to animate virtual handball players thanks to motion capture (Ménardais, Multon, & Arnaldi, 2002). This framework generated trajectories without occlusions that could be played in real time. Moreover, the captured trajectories were adapted to the virtual player's morphology. Indeed, the real subject and the virtual one generally had different sizes and morphologies. The global framework also enabled us to adapt the original motion to the virtual actor while ensuring foot contact with the ground.

This framework was organized as follows. First, it enabled us to load a motion capture file with its corresponding original skeleton (linked to the real subject who performed the motion). Second, we ran the reconstruction process that recovered the missing points while accounting for anatomical constraints. These constraints were mainly distance constraints between two points belonging to the same body segment. Third, we loaded the skeleton of the virtual player that is then animated. The reconstructed trajectories were applied to this last skeleton by computing the required quaternions for each articulation. At this step, we activated constraints such as foot contact with the ground and continuity with other compatible motions. For example, if the studied motion *m1* had to be sequenced with a run *m2,* a left foot strike at the end of *m1* should correspond to a left foot strike at the beginning of *m2.* The resulting motion was filtered with a second-order Butterworth filter with a 10 Hz cutoff frequency. At the end of this process, the motion was stored automatically as a set of keyframes that were directly used for computer animation.

Several captured motions were necessary to animate a virtual handball player: running, walking, and various handball throws. These throws corresponded to the ones performed by the handball player during the preliminary experiment. As the capture area did not cover all the motion from the start to the ball release, including the running phase, we captured some of these motions separately from the throw itself. Consequently, the motions were sequenced in real time by the animation engine. In conclusion, we paid attention to the transition between these elementary motions. To this end, the animation engine was able to synchronize several movements. This engine was embedded in a virtual reality platform GASP (general and simulation platform) (Donikian, Chauffaut, Duval, & Kulpa, 1998). GASP is a software framework that enables communication and interaction between entities belonging to a virtual environment. This communication can be achieved in two ways:

- *dataflow:* Each entity owns its own inputs, outputs, and control parameters. The inputs of one module can be dynamically plugged to the outputs of another one during the simulation. For example, when the ball was attached to the handball player's hand, the output coordinates of his hand were transmitted to the ball, whereas this link was broken after ball release.

- *events:* GASP offers services to manage signals, events, and event listeners. Events were used to model the ball release and the change of motion (for example, the move from running to throwing when entering the 9 m area).

Our animation engine used three entities as depicted in Figure 3:

- *the thrower:* This module represented the virtual thrower. First, it dealt with his behavior. To this end, it managed the scheduling of his motions. Secondly, this entity managed the 3D animation of the virtual thrower. It used the captured motion to get the quaternions for each articulation. Moreover, it handled the transition between them to have a realistic animation.
- *The throw configurer:* This entity dealt with the interaction between the new motion of the thrower and the trajectory of the ball. Each time the thrower played a motion, this module accessed the database to get the following parameters right:
    - *active:* In our application, this Boolean specified whether the new motion of the thrower had an effect on the ball trajectory. It was the case during a throw or during a run when the ball is held. (The parameter is set to "true.") On the contrary, after a throw, the thrower ran while the ball was following its own trajectory. In that case, this parameter was set to "false," and all the other parameters were ignored.
    - *thrown:* At the beginning of the motion (if the "active" parameter was set), the ball was in the hand of the thrower. This parameter was a Boolean that specified whether the ball had to be thrown. Indeed, during the run before the throw, the virtual thrower kept the ball in his hand. In this case (parameter set to "false"), the following three parameters were not used.
    - *ball release event:* During a throwing motion, it corresponded to the time of ball release.
    - *ball speed:* It was the ball speed during its flying phase, after release.
    - *ball destination:* It was the place where the ball entered the goal.
- *the ball handler:* After getting all the parameters from the previous module, this entity managed the 3D trajectory of the ball. During a motion in which the ball was in the hand of the thrower, this module obtains the wrist position of the thrower. The position of the ball corresponded to the wrist one.

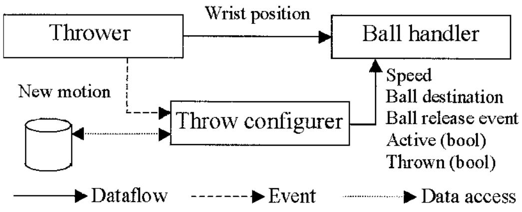

Figure 3. *Animation engine.*

3 Real Handball Goalkeeper vs. Virtual Handball Player

In the second part of the experiment, we placed the real handball goalkeeper in a virtual stadium (see Figure 4) to play against a virtual thrower (Figure 5). We used a reality center comprising a SGI Onyx2 InfiniteReality with three pipes and three Barco 1208S videoprojectors used on a cylindrical screen (with a radius of 3.80 m, a height of 2.38 m, and a 135° field of vision). To obtain a real goalkeeper's behavior, we reconstructed an environment as real as possible by reproducing visual landmarks, well known in handball. One of the most important landmarks was the goal itself that was physically placed in the reality center. This goal was placed around the goalkeeper's position that also corresponded to the position of the virtual camera. First, to set up the position of the virtual camera, we placed a temporary landmark into the virtual environment. It was placed at a distance from the virtual goal corresponding to the one between the real goal and the screen. Then we moved the camera until the landmark intersected the display. The remainder of the virtual stadium was modeled to fit the dimension of a real stadium.

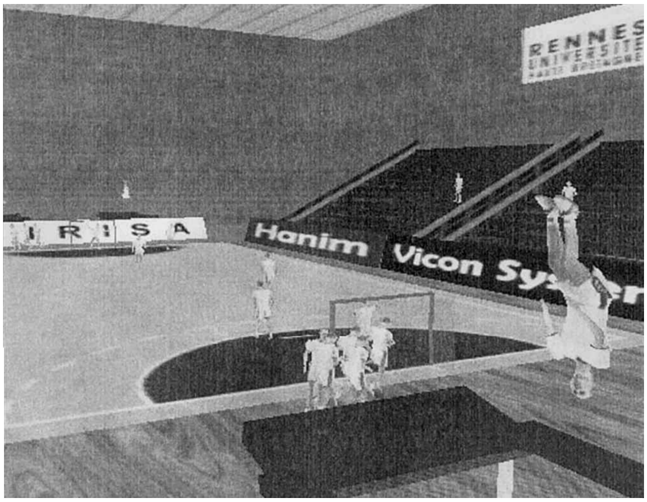

Figure 4. *Virtual stadium.*

Figure 5. *Virtual thrower vs. real goalkeeper.*

Once the real and the virtual world were calibrated, we focused on the movement of the virtual ball, which was another important parameter that engendered goalkeeper reactions. This ball had to be textured as a real ball, and its trajectory after release had to satisfy the mechanical laws. To this end, three parameters were necessary: the location of the ball release in space, the ball speed at release, and the location of the intersection point with the goal. To best fit the original throw, we measured the actual ball speed for each studied throw with a radar gun (from Stalker Radar). In the real experiment, the ball release was determined with the motion capture system that provided us with the location of the ball at release for all the studied throws. Finally, we subdivided the goal into several areas including the upper-left corner and the upper-right corner. In the real world, the players shot only on three of these areas. The other areas were used to create new situations by changing artificially the ball destination for a given studied throw. The application of this method was to determine if the goalkeeper reacted differently and, consequently, if he took information from only the ball's trajectory or from other parameters.

To study the different throws and the resulting goalkeeper actions, we again used the Vicon370 motion capture system. The reality center and the motion capture system were not physically synchronized, and no start signal was given to the goalkeeper, who naturally reacted to the virtual thrower actions.

For the virtual experiment, one goalkeeper participated in this pilot experiment and was equipped with the markers. The subject took his place in the reality center, inside a goal that was physically placed in the room. We familiarized the goalkeeper with the virtual environment and all the equipment used for the experimentation (3D glasses, markers, and the virtual environment). As in the real experiment, no particular instruction was given to the subject. He only had to react as in a real game without restriction. Then we asked the goalkeeper to stop 24 throws that were randomly chosen among all the available captured throws. These captured throws were divided into three main categories:

- *6 m throw without jumping:* using four captured throws and another faked one (the ball destination was artificially changed)
- *6 m throw while jumping:* using four captured throws
- *9 m throw without jumping:* using three captured throws

All these throws were played two times randomly to prevent the goalkeeper from recognizing the throw

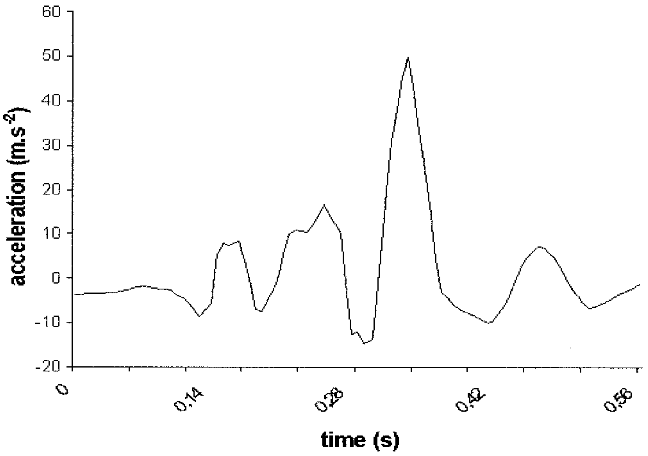

Figure 6. *Acceleration of arm COM for a motion.*

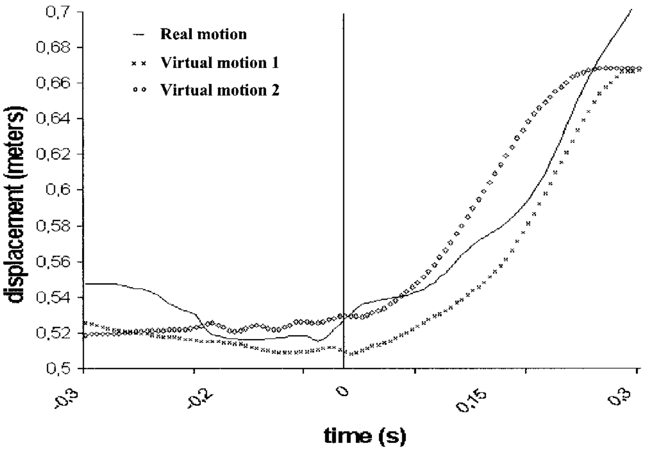

Figure 7. *Center of mass displacement of the right arm along the z axis.*

used. Between each throw, the subject returned to his natural position and waited for the next trial, without any information about the following trial.

4 Results

The main goal of these experiments was to verify if the movements performed by the goalkeeper in the real and virtual environments were similar and, thus, if virtual reality could be used in sport as a training and research tool. In our study, we focused on biomechanical analysis. To this end, we chose to compare the arm and leg displacements in the real and the virtual environment. More specifically, we studied the arm and the leg center of mass (denoted *COM* in the remainder of the paper) displacement in the total body COM reference frame. We selected the arm and the leg COM because not only the hands or the feet were used to catch the ball but the whole limbs. The COM was computed with anthropometrical tables (Winter, 1979). To compare trajectories obtained in the real and virtual environment, we had to ensure that these data were compatible. To compare two trajectories, we determined an event that enabled us to synchronize the two motions. In a handball throw, the ball release could be such an event. However, as there was no physical synchronization between the motion capture system and the reality center, the ball release in the virtual world could not be viewed with the motion capture system. Consequently, we chose to synchronize the trajectories according to the beginning of the goalkeeper's reaction. To this end, we computed the acceleration of the goalkeeper's arm in all the studied trajectories. A peak of acceleration was identified in all the resulting accelerations and represents the beginning of the goalkeeper's action. (See Figure 6.) Once this event was detected for all the studied trajectories, we selected a time window ranging from −0.3s to +0.3s around it.

We studied 24 throws divided into three main categories: from 6 m with and without jumping and from 9 m without jumping. For each category, four ball destinations were considered, including all the goal's corners. As a consequence, the goalkeeper was confronted randomly several times with the same situation. For one of all these possible situations, Figure 7 presents the displacement of the arm COM along the *z* axis (vertical axis) knowing that this arm was going to intercept the ball. For each studied situation, all the considered COM trajectories had the same shape, playing in a real or a virtual handball environment. Hence, there was no significant difference between the motions for the real and the virtual situations.

Table 1 describes the results obtained by considering

Table 1. *Kinematic Variations of the Arm's Center of Mass Along the Vertical Axis*

Motion	Arm initial position (m)	Arm final position (m)	Displacement (m)	Difference from the real action (%)	Correlation coefficient (R^2)
6 m					
Real 1	0.546	0.706	0.16	**	
Virtual 1	0.522 ± 0.03	0.667 ± 0.00	0.145 ± 0.04	9.4 ± 2.5%	0.98 ± 0.01
Real 2	0.542	0.400	0.142	**	
Virtual 2	0.528 ± 0.04	0.39 ± 0.03	0.136 ± 0.02	4 ± 1.2%	0.99 ± 0.00
Real 3	0.536	0.661	0.125	**	
Virtual 3	0.520 ± 0.05	0.632 ± 0.04	0.112 ± 0.01	10.4 ± 0.8%	0.97 ± 0.01
Real 4	0.539	0.382	0.157	**	
Virtual 4	0.525 ± 0.01	0.355 ± 0.03	0.17 ± 0.02	8.2 ± 1.2%	0.98 ± 0.01
6 m + jump					
Real 1	0.535	0.336	0.199	**	
Virtual 1	0.516 ± 0.01	0.330 ± 0.02	0.186 ± 0.01	6.5 ± 0.5%	0.98 ± 0.00
Real 2	0.543	0.722	0.179	**	
Virtual 2	0.533 ± 0.02	0.702 ± 0.05	0.169 ± 0.03	5.6 ± 1.6%	0.99 ± 0.00
Real 3	0.551	0.350	0.201	**	
Virtual 3	0.525 ± 0.03	0.340 ± 0.02	0.183 ± 0.00	8.7 ± 0.2%	0.97 ± 0.01
Real 4	0.538	0.703	0.165	**	
Virtual 4	0.520 ± 0.05	0.672 ± 0.01	0.152 ± 0.04	7.8 ± 2.5%	0.98 ± 0.01
9 m					
Real 1	0.545	0.695	0.15	**	
Virtual 1	0.526 ± 0.04	0.662 ± 0.03	0.136 ± 0.01	9.3 ± 0.7%	0.97 ± 0.01
Real 2	0.537	0.712	0.175	**	
Virtual 2	0.517 ± 0.01	0.685 ± 0.00	0.168 ± 0.01	4.5 ± 1%	0.98 ± 0.01
Real 3	0.549	0.704	0.155	**	
Virtual 3	0.528 ± 0.03	0.670 ± 0.02	0.142 ± 0.01	8.4 ± 0.6%	0.97 ± 0.00

the arm's movement. In this table, the three situations appear in bold font. For each situation, we give all the throws in the real experiment together with their corresponding throws in the virtual environment. Each throw in the virtual experiment was compared to the real one through the initial and final arm position in the global COM reference frame, the arm's displacement in meters, the difference between the arm's displacement in the real and virtual throw in percentage, and the correlation between the shape of the movements in the real and virtual experiments.

Table 2 contains the same kind of information but for the leg.

The worst difference was about 9.4 ± 2.5% (that is to say 11.9% at worst) along the z axis for the arm's COM motion.

In addition, for some trials, we artificially modified the ball's trajectory to make it reach the opposite corner without changing the handball thrower motion. Each time, the goalkeeper tried to stop the ball on the original side. His repeated mistakes were really interesting because they showed that the goalkeeper did not take

Table 2. *Kinematic Variations of the Leg's Center of Mass Along the Lateral Axis*

Motion	Leg initial position (m)	Leg final position (m)	Displacement (m)	Difference from the real action (%)	Correlation coefficient (R^2)
6 m					
Real 1	0.247	0.515	0.268	**	
Virtual 1	0.268 ± 0.04	0.518 ± 0.03	0.251 ± 0.01	6.7 ± 0.3%	0.98 ± 0.00
Real 2	0.253	0.522	0.269	**	
Virtual 2	0.263 ± 0.02	0.520 ± 0.01	0.257 ± 0.01	4.5 ± 0.4%	0.99 ± 0.00
Real 3	0.245	0.515	0.27	**	
Virtual 3	0.261 ± 0.00	0.510 ± 0.02	0.249 ± 0.02	5.8 ± 0.7%	0.97 ± 0.01
Real 4	0.271	0.523	0.252	**	
Virtual 4	0.258 ± 0.01	0.500 ± 0.01	0.242 ± 0.01	3.9 ± 0.4%	0.98 ± 0.01
6 m + jump					
Real 1	0.244	0.519	0.275	**	
Virtual 1	0.250 ± 0.03	0.506 ± 0.02	0.256 ± 0.01	6.9 ± 0.4%	0.98 ± 0.00
Real 2	0.262	0.525	0.263	**	
Virtual 2	0.255 ± 0.02	0.503 ± 0.04	0.248 ± 0.02	5.7 ± 0.7%	0.98 ± 0.01
Real 3	0.266	0.522	0.256	**	
Virtual 3	0.259 ± 0.00	0.502 ± 0.03	0.245 ± 0.03	5.7 ± 0.7%	0.97 ± 0.00
Real 4	0.240	0.478	0.238	**	
Virtual 4	0.253 ± 0.01	0.472 ± 0.01	0.219 ± 0.00	8 ± 0.0%	0.98 ± 0.00
9 m					
Real 1	0.260	0.513	0.253	**	
Virtual 1	0.262 ± 0.02	0.504 ± 0.03	0.242 ± 0.01	4.4 ± 0.4%	0.98 ± 0.01
Real 2	0.265	0.505	0.24	**	
Virtual 2	0.252 ± 0.03	0.475 ± 0.01	0.22 ± 0.02	7.3 ± 1%	0.98 ± 0.01
Real 3	0.243	0.520	0.277	**	
Virtual 3	0.251 ± 0.01	0.514 ± 0.02	0.263 ± 0.01	5.1 ± 0.4%	0.97 ± 0.00

information from the ball trajectory but from the thrower's motion.

5 Discussion

In this paper, we presented a virtual reality experiment that involved a real goalkeeper and several virtual throws. The goal of this paper was to verify if the goalkeeper's reactions in the virtual environment were similar to those captured in a preliminary real experiment. Usually, presence in a virtual world has been quantified using questionnaires and statistical analysis (Slater, 1999). Usoh, Catena, Arman, and Slater (2000) demonstrated that such studies are limited for a comparison between real and virtual environments. In our study, we were particularly interested in the movements. So, we used biomechanical analysis. Our last goal was to produce a presence index. The motions of the virtual thrower were captured during the preliminary experiment and adapted to fit the virtual thrower's skeleton. The ball was driven by a mechanical model whose inputs were the initial position at release, the velocity vector norm, and the destination in the goal. Our results showed that the goalkeeper's movements in the virtual environment were similar to those captured in the real experiment. This result was obtained for all the studied situations including three different throws, each with two different destinations.

Of course, we tested this experiment with only one subject who played at a national level, but the promising results encourage us to repeat this experiment with a larger set of goalkeepers and throwers. These kinds of results are very important for sport applications. Indeed, this tool offers new ways of investigation to understand how goalkeepers react to throws. One of the most important points is to reproduce exactly the same situation and verify if the goalkeeper always reacts in the same way. Another important point is to ensure that the synthetic motions are realistic enough to engender realistic reactions. For our study, we used a 29-DOF model whose trunk was modeled as a unique body segment. This simplified model was enough to make the goalkeeper react as he would against a real thrower. Nevertheless, future work will tend to improve the geometric model and the skeleton quality (such as adding fingers flexion and other rotational joints to the trunk).

We also experimented with a few fake throws: a real motion for which the ball should go to the left corner whereas we made the ball go to the other side. The goalkeeper each time tried to stop the ball on the original side and was tricked by our modification. This was a very important point, suggesting that the goalkeeper took information from the thrower's motion and reacted before the ball was released. Indeed, it was known that, at a high playing level, goalkeepers do not take information from the gaze of throwers but perhaps from the ball trajectory. So, this first result was really interesting. This experiment could not be conducted with real throwers because changing the ball direction also involved changing the movement. Hence, it was quite impossible to verify this hypothesis with real experiments.

This system provides trainers with new tools to evaluate the goalkeeper's performance and training. In addition, this tool offers a way to train goalkeepers against future opponents whose motions are designed according to old recorded games (for example, from videotapes and with the help of an animator).

An improvement on this technique should add the possibility for the goalkeeper to interact with the thrower. To this end, we need a real-time motion capture system that would be able to analyze the goalkeeper's reactions in order to change the thrower's strategy. In some cases, the goalkeeper anticipates the thrower's action by voluntarily blocking a side of the goal. Then the thrower is encouraged to throw the ball at the opposite side. During our virtual experiments, the goalkeeper explained that he was tempted to try this strategy. Nevertheless, in this version, there was no change in the virtual thrower's behavior. Future work will tend to overcome this limitation by coupling to the reality center a real-time motion capture system and a simple behavioral model. Adding such a system will also make it possible to verify if the goalkeeper intercepts the ball by performing a collision detection between the ball's geometry and the goalkeeper's upper limb. We are currently working on such an experiment.

Another possible extension of this tool is to offer the trainer and the goalkeeper a posteriori view of a camera placed anywhere in the 3D world. For example, the camera could be placed to see at the same time the motions of the thrower and the goalkeeper to observe the interaction between them. Hence, it would be possible to visualize the movements of the goalkeeper for all the situations. Consequently, we can conduct the opposite experiment by examining how a thrower should react to a goalkeeper's motions for all the studied situations. We could also use a distributed environment to make two real players interact through two distant reality centers as in Noser's experiment (Noser, 1996). Such a technique may allow distant players to train each other while recording their motion in 3D for a posteriori analyses.

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