

Visualization of Human Motion via Virtual Reality Interface and Interaction based on It

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Abstract: This paper presents the concept of *ecological* sports training and the initial developments based on biomechanics analysis, VR technologies, and visualization of interaction. Computation algorithms in robotics have been applied to biomechanics analyses including muscle force estimation. These technologies are widely used for the *self*-biomechanics training, in which an athlete accesses and evaluates the analyzed results on his/her own motions and will necessarily move toward the *ecological* training that considers interactions with the counterpart and the environment in a sport game. We develop a VR visualization system of musculoskeletal analysis that provides a realistic experience of the interactions to an athlete. We also report an initial evaluation of the interactions with the virtual counterpart in the virtual environments through the VR system.

1 INTRODUCTION

Biomechanics is the basis of sports training. Technologies have been developed and widely used to facilitate the self-biomechanics training, which implies a training where an athlete by oneself accesses scientific evaluation and objective advice (Yoo et al., 2020) (Maroto-Izquierdo et al., 2019). The analysis of musculoskeletal activity exists as one of the methods of motion analysis (Hill, 1938) (Stroeve, 1999) (Nakamura et al., 2005). And an application is being developed to visualize these results so that they can be easily understood by non-specialists, subjects themselves (Murai et al., 2010). However, since many sports are played not only by oneself but also by competing against other competitors, in teams, or by interacting with the surrounding environment, analysis of only one subject is insufficient. Therefore, it is necessary to develop ecological training that includes others surrounding the subject. Ecological training is a type of training that involves not only oneself, but also others and the environment proposed by Davids and Handford (Davids et al., 1994) (Handford et al., 1997). The possibility of stimulation from environments other than oneself is called affordance and is proposed by Gibson (Gibson, 2014). By recreating an environment with an affordance like that of a game, the player can train with an understanding of not only



Figure 1: Visualization of musculoskeletal analysis on a taekwondo kick motion measured by IMU-based motion capture suite.

oneself but also the surroundings. In this study, we define it as training that is conducted by presenting others and environments other than oneself.

When ecological training is conducted, it is inadequate to reproduce the actual game or training environment by using conventional monitors for presentation. But the use of a VR headset during the presentation increases the realism of the environment and helps to build a training method that replicates the environment surrounding the player. Reproducing the surrounding environment allows the subject

to play under the influence of them and us (including the subject) to analyze their movements. Some studies of VR training and analysis has been conducted by recreating environment. In sports, analysis of the difference in skills between advanced and novice players has been conducted, as well as controlled experiments on the level of improvement when using VR and when not using VR (Hosp et al., 2020) (Petri et al., 2019) (Kimura et al., 2018). In other fields, VR simulators for heavy machinery such as construction site cranes and forklifts are being developed (Technologies, 2021), and research is being conducted on drilling drill proficiency training (Zhang, 2017).

In order to support the ecological training method, this study aims to develop a training method in which the player is presented with a space that reproduces the competition opponent and the surrounding environment using VR, and the player can compete under the influence of each other and analyze the movement. In this case, the results of musculoskeletal analysis, which is the result of biomechanical analysis of the athlete, can be presented for use in ecological training. In this report, we developed a method to visualize the results of biomechanical analysis presented to players. In addition, we verified the reproducibility of the interaction with the opponent and surrounding environment in the VR space compared to the real environment by bidirectional walking.

2 MUSCULOSKELETAL MODEL VISUALIZATION

2.1 Visualization Flow

In this study, we use a wire approximation model of muscle (Nakamura et al., 2005). This model uses inverse kinematics to calculate the position and posture of the skeleton from the 3D positions of markers that represent the positions of body parts. The muscle wires are basically attached to the skeleton, and from the obtained skeletal motion and mechanical parameters, the wire tensions are optimized using inverse dynamics, assuming that the sum of the squares of the wire tensions is minimized.

The musculoskeletal rendering method using this wire model (Murai et al., 2009) was based on OpenGL, which doesn't allow for fast and detailed real-time rendering and display in VR headset. To solve this problem, we implemented a fast-rendering method using Unity, which is a development environment that supports a variety of platforms. In addition, in the real-time rendering of muscles, polygon rupture

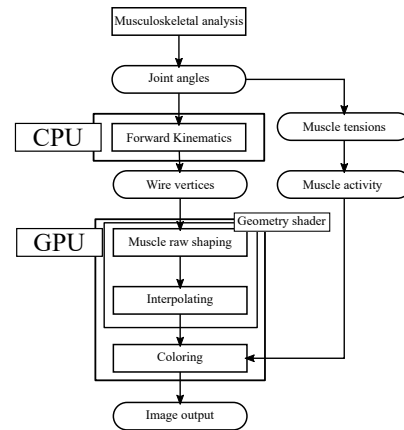


Figure 2: Musculoskeletal visualize flow. Polygon position calculation is divided to CPU part and GPU part.

occurs when rendering diffraction shapes, causing a sense of discomfort, but we have solved this problem by rendering detailed muscle shapes. And by using geometry shader which increases the number of polygons in GPU simultaneously, we distribute cost between the CPU and GPU and improve processing speed. The flow of the visualization process is shown in Figure. 2. Joint angles and muscle tensions are obtained from the results of musculoskeletal analysis. From the joint angles, the wire vertices of the muscle can be obtained by solving forward kinematics on the CPU, which are input to the GPU to calculate the muscle shape using a geometry shader. Muscle tensions are used as input to the GPU for coloring them. The final screen output is obtained through the above processing.

2.2 Creation of Muscle Shape Polygons

We create a muscle-like appearance while avoiding tearing of the diffraction shape by using the wire muscle model (Nakamura et al., 2005). Let the wire vertices of the muscle be p_0, p_1, \dots, p_{n-1} in order. p_0 is the origin point and p_{n-1} is the arrest point. The other vertices are defined as passing points. Obtain a circle C_i orthogonal to the line connecting p_i and p_{i+1} . C_i is represented by two vectors u_i and v_i that are orthogonal to each other.

$$t = p_{i+1} - p_i \quad (t = (t_x, t_y, t_z)) \quad (1)$$

$$a_i = (0, t_z, -t_y) \quad (2)$$

$$b_i = (t_y^2 + t_z^2, -t_x t_y, -t_x t_z) \quad (3)$$

$$u_i = \frac{a_i}{|a_i|}, v_i = \frac{b_i}{|b_i|} \quad (4)$$

The radius of this C_i is changed to create the spindle shape of the muscle. To reproduce the spindle

shape of the muscle, the radius is calculated using the quadratic function.

$$f(x) = \frac{p}{4}(x^2 - a^2)^2 \quad (5)$$

$f(0) = pa^4/4$ is the maximum radius of the muscle, which is proportional to the maximum force of the muscle. The spindle shape is created as shown in Figure. 3. If one of the two points representing the line l_i is the origin or arrest point, a half spindle-shaped polygon is created; otherwise, a cylindrical polygon is created. At this time, there is a gap between the polygons near the transit point due to the diffraction shape as shown in Figure. 4.

To fill this gap, we create new triangular polygons by connecting the polygons on the two orthogonal circles on the passing point. Let the two orthogonal circles on the passing point be C_i and C_{i+1} , and the unit vectors representing each circle be u_i, v_i and u_{i+1}, v_{i+1} . At this time, the degree of the polygon gap changes depending on the bending angle of the wire on the target passing point. Therefore, the interpolation method is changed according to the bending angle, and appropriate interpolation is performed.

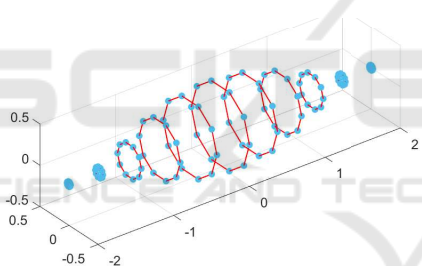


Figure 3: Shuttle 3d polygon points. Each circle radius is due to $f(x) = p(x^2 - a^2)^2/4$.

2.2.1 When the Bending Angles is 120° or More

Let the radius of the orthogonal circle be r . At this time, the polygon vertices on C_i are obtained when

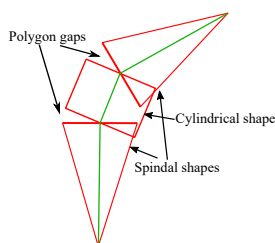


Figure 4: Polygon gap by the wire bending. Green line shows wired muscle. Red triangles and rect show created muscle polygons.

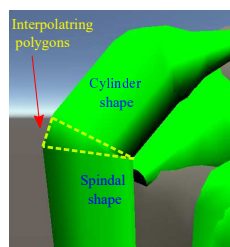


Figure 5: Polygon gap on the passing point is interpolated.

the circles are approximated by regular n-gon.

$$q_{ij} = p_i + r(u_i \cos 2\pi \frac{j}{n} + v_i \sin 2\pi \frac{j}{n}) \quad (0 \leq j < n) \quad (6)$$

Select the vertices $t_{k,0}, t_{k,1}, t_{k,2}$, which consist the triangle polygon t_k , from on each orthogonal circle so that the each distance between the polygon vertices is minimized.

$$t_{k,0} = q_{i,j} \quad (7)$$

$$t_{k,1} = q_{i+1,j+1} \quad (8)$$

$$t_{k,2} = \begin{cases} q_{i+1,j} & (0 \leq k < n) \\ q_{i,j+1} & (n \leq k < 2n) \end{cases} \quad (9)$$

This selection of vertices interpolates the gap with a total of $2n$ triangular polygons as shown in Figure. 6.

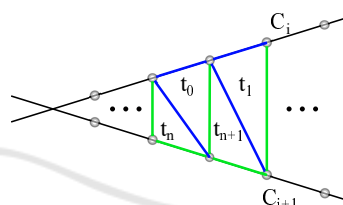


Figure 6: Polygon gap creation from orthogonal circles on the passing point. Each triangle has 3 polygon vertices on the circles.

2.2.2 When the Bending Angle Is Less than 120°

When the bending angle is 120° or more, a triangular polygon was constructed by connecting the polygon vertices on the C_i and C_{i+1} to hide the crack, but if the angle is close to an acute angle, the interpolation is rapid and unnatural. So, we create an intermediate circle C_m and perform a gentle interpolation. Let l_i and l_{i+1} be the lines that make up the wire that intersects at the passing point and let n_i and n_{i+1} be the directional vectors on the lines. The unit vectors u_m, v_m that represent the orthogonal circle C_m which divides the wire segment are obtained as follows. Interpolation is by filling two gaps between C_i and C_m, C_m , and C_{i+1} .

$$a_m = n_i + n_{i+1} \quad (10)$$

$$u_m = \frac{a_m}{|a_m|} \quad (11)$$

$$v_m = n_i \times n_{i+1} \quad (12)$$

2.3 Fast Rendering by Geometry Shader

In this way, natural muscle polygons with no tears can be created as shown in Figure. 5. The process of cre-

ating muscle polygons is performed using the geometry shader on GPU. The geometry shader is a process that takes polygon vertices as input and increases the number of vertices. Parallel processing on the GPU allows for fast polygon increment processing.

3 SPORT MOTION PRESENTATION ON VR WORLD

3.1 Motion Measurement and Musculoskeletal Analysis

We conducted measurement and presentation to reproduce the interaction in VR world with an opponent by taekwondo motion, which is one of the interpersonal sports. We measured taekwondo motion of one player and one coach by IMU-suit motion capture and applied musculoskeletal analysis. The obtained musculoskeletal motion was presented on a head-mounted display to taekwondo athletes, coaches, who have knowledge of taekwondo for evaluation. The IMU suit was used in the measurement experiment of taekwondo. The result of musculoskeletal analysis by applying inverse kinematics and inverse dynamics to the measured motion is shown in Figure. 1.

3.2 Presentation on VR World

The measured motion is visualized in the VR world using the musculoskeletal analysis result drawing method described in Chapter 2 and presented to the subjects wearing the VR headset. The head-mounted display used for the presentation was the Oculus Quest2 by Oculus. The subjective evaluation and response of the subjects during the presentation are shown below.

- The musculoskeletal presentation using a display was not so good, but the VR presentation using headset had a completely different sense of scale and gave a sense of realism to the kicking.
- You could observe the motions up close, and although you could see the differences in the kicks of the players on the display, I could see the differences even more.
- The subjects felt that measuring the opponent's kicks in competitions and presenting the measured motions in VR would be more useful than research using displays to learn the opponent in advance.

3.3 Discussion

From the impressions and evaluations, it is considered that the musculoskeletal motion presentation can reproduce the interaction with the opponent as in the real world. By using this interaction, we can reproduce the movements of the opponent, which is difficult to achieve in the real world, and lead to more efficient training than before.

4 MEASUREMENT INTERACTION ON REAL WORLD

To reproduce human-human interaction in the VR world, we conducted 3D integrated measurement experiments of humans and the environment. The motion obtained from the musculoskeletal analysis of the measured data is presented in the VR space.

4.1 Measurement Methods

4.1.1 Motion Capture

In this experiment, we use video motion capture (VMocap) developed by Ohashi et al. (Ohashi et al., 2018), which estimates the 3D positions of joints by capturing images with multiple cameras and using the probability of the existence of the subject's joints obtained by Openpose (Cao et al., 2017).

4.1.2 Environment Measurement

VisualSLAM (Moulon et al., 2012) is a method for estimating the 3D positional relationship between the camera that captured the image and the feature points based on the correspondence between images of feature points on the image, using multiple images of the object as input. The application of photogrammetry, Meshroom (AliceVision, 2018), can be used to reconstruct 3D models of the environment.

4.2 Conditions

The measurement space is shown in Figure. 7, where there is an obstacle like a desk in the center of the environment, and subjects passing near the obstacle and interacting with the environment. The 3D model of the measurement environment was created using Meshroom in advance, and the measurement was performed in a situation where subjects were passing each other, and VMocap was used to obtain the motion of the subjects. We instructed two subjects to

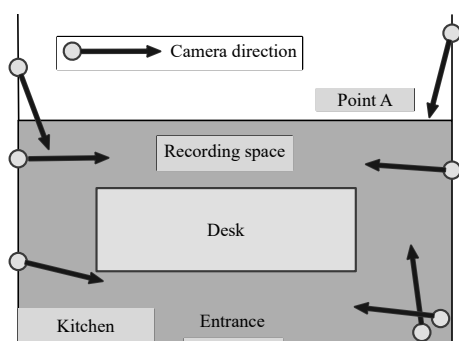


Figure 7: Recording area, which has entrance and desk at the center. 7 cameras covered area.

perform the following walking motions in a real environment and asked them to pass each other.

- The subject who walks clockwise around the desk from the entrance is designated as Subject A. Subject A is asked to pick up the pencil case on the desk and proceed to the entrance again.
- The subject who passes subject A is called subject B. Subject B was given no instructions other than to pass each other.

4.3 Reconstruction Result

Figure. 8 is the result of subject’s key points detection by Openpose. Key points are well detected in the environment. The musculoskeletal motion and environment estimation results of two subjects passing motion is shown in Figure. 9.

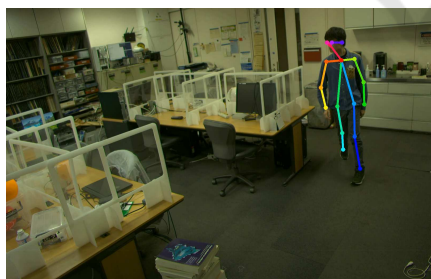


Figure 8: Subject key points estimation result.



Figure 9: Musculoskeletal motions of the passing motion in the environment.

5 INTERACTION REPRODUCTION ON VR WORLD

5.1 Presentation Method

The data measured in the previous chapter are reproduced in the VR world, and the presentation experiment is conducted to reproduce the passing motion of the subject in the real space and the VR world. For the presentation, we used the Oculus Quest2.

5.2 Conditions

The subjects are asked to reproduce the following actions in the real world measured in the previous section.

1. The subject lonely starts at the entrance, moves clockwise around the desk in the center of the environment, retrieves the pencil case, and returns to the entrance.
2. Passing motion with a person starting from the Point A and proceeding to the washroom.
3. Passing motion with a person starting from the entrance and proceeding clockwise around the desk

Since Motion 1 is performed by only one person, the VR presentation does not use the motion measured in the previous section. In order to compare whether the behavior changes depending on the presentation of the person passing by, we used the presentation with muscle rendering and the presentation with only the skeleton without muscle rendering in Motion 2 and 3. The conditions used in this study are the following motions measured in the previous section.

- a. Motion 2 with muscle drawing
- b. Motion 2 without muscle drawing
- c. Motion 3 with muscle drawing
- d. Motion 3 without muscle drawing

A total of five subjects participated in the study.

5.3 Results

5.3.1 Trajectory Comparison

Figure. 10 is the walking motion of a single person moving clockwise around a desk. The red line shows the trajectory in real world, blue lines show the trajectory in VR world. Figure. 11 is a superimposed drawing of the walking motion in the VR world and the walking motion in the real world under conditions a, b, c and d.

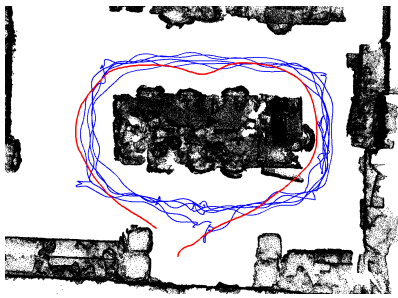


Figure 10: Trajectories of walking around desk (Motion 1). Red line shows trajectory measured in real world by video motion capture. Blue lines show subjects trajectory.

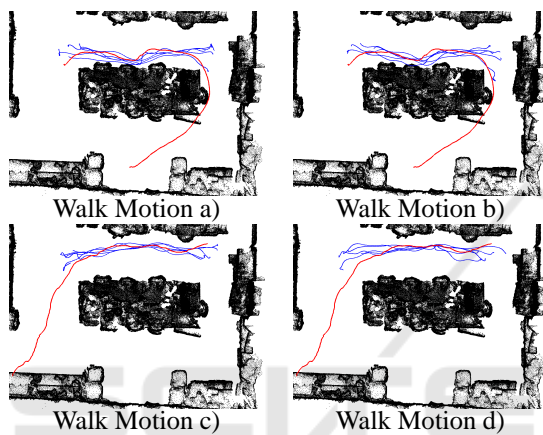


Figure 11: Trajectories of crossing paths with Opponents a), b), c), d).

In the clockwise walking motion in the environment (Motion 1), the trajectory in the real world progresses smoothly around a corner, while the trajectory in the VR world tends to make a right turn. The trajectory in the VR world remains in line with the desk for most subjects, while the trajectory in the real world leaves the desk immediately after the acquisition of the pencil case. Comparing the trajectories in the VR space in condition a and b, the trajectories in condition a showed less variation. In the action of walking pass each other while retrieving the pencil case (Motion 2), the trajectories in the real world and in the VR world are almost the same in the Motion 3 of passing a person who acquires a pencil case, especially in the middle of the trajectory where they pass each other. The trajectories in the VR space for condition c and d were compared, and as in the case of Motion 2, the trajectories in condition c showed less variation.

5.3.2 Distance and Gaze Direction Vector against Opponent

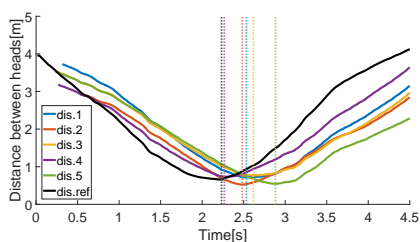
We focused the change on the distance between the subject and the passing opponent as an interaction. Figure. 12 is a time series graph of the distance between the subject's head and the passing opponent projected onto a horizontal plane. The vertical line indicates the timing of the minimum distance between the subject and the passer-by. View the distance graph in the beginning. In all conditions, the timing of the minimum distance to the opponent is faster in the case of passing each other in the real world. In addition, in conditions a and b, the minimum distance to the opponent tends to be smaller in the case of passing each other in the VR world.

Next, we focused on the gaze direction graph. Figure. 13 is a time series graph of the gaze vector angle against the passing opponent. The closer the angle is to 0° , the more the subject is gazing at the opponent. In all the figures, we can see that the subjects in the VR world gaze at the opponent longer. In addition, in conditions a and b, the subjects in the real world do not gaze at the other person for a long time, such as immediately removing their gaze after gazing at the other person for about one second from the beginning of passing, while the subjects in the VR world tend to gaze at the other person until just before passing.

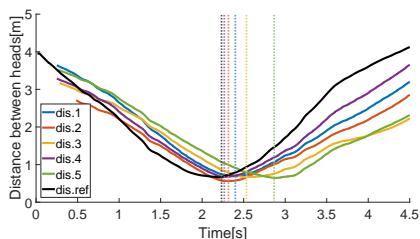
5.4 Discussion

Using the walking motion in the real world measured in the previous section and the environment information reconstructed by VisualSLAM, we conducted a reproduction experiment in the VR world to compare the walking motion in the real world and the walking motion in the VR world. Awkward clockwise walking in VR world (Motion 1) is thought to be because the subject did not fully grasp of the space in the VR world and felt resistance to moving while walking. In addition to grasping of the space, the actual environment in which the VR reproduction experiment was conducted was surrounded by walls, and the subject is controlled not to collide with such real obstacles. This movement restrictions are also shown in the time series graphs of the distance and direction of gaze of the passers-by, and the time at which large changes occur in the graphs is often later in the VR world than in the real world.

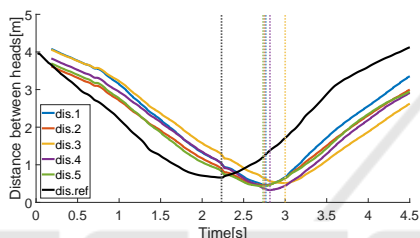
When we compared the time when the opponent in VR world was visualized with muscles included and the time when only the skeleton was visualized, the variation of the path was less when muscles were included. The reason for this is that including muscles



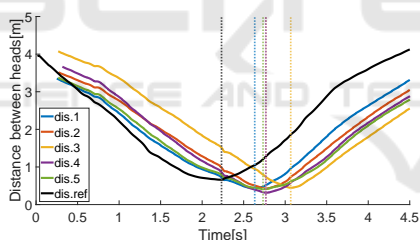
Walk Motion a



Walk Motion b



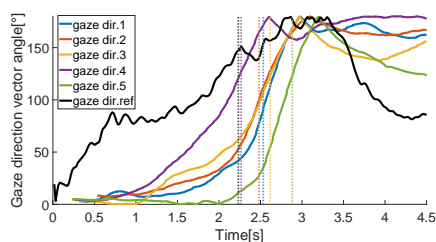
Walk Motion c



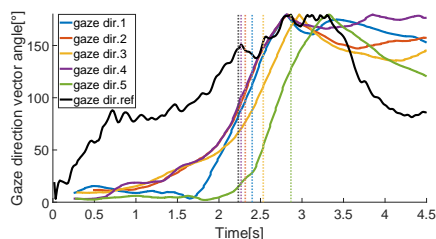
Walk Motion d

Figure 12: Solid lines show time series change of distance between subject and opponent. Dotted vertical lines show the timing of minimum distance to the opponent.

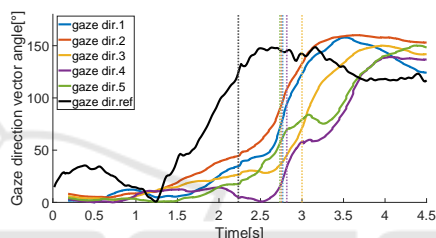
increased the existence of the opponent and narrowed the range of the subject's choice of path. In addition, the subjects thought that they were passing between a desk and the opponent in the environment, and the environmental information was given close to the reality. Although the presence or absence of the muscle visualizing influenced the choice of the path, the minimum distance to the passing partner was not different. It did not influence the timing of the actual crossing, when the opponent is reflected at the edge of the field of vision, making it more difficult to see than in the center of the field of vision. When we compared how long the subjects gazed at the opponent, the subjects in the VR world tended to gaze at



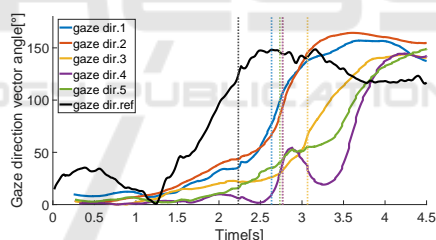
Walk Motion a



Walk Motion b



Walk Motion c



Walk Motion d

Figure 13: Solid lines show time series change of angle between the line of sight and the line connecting subject and opponent. Dotted vertical lines show the timing of minimum distance to the opponent.

him longer. It is thought that it was necessary to observe him for a long time when passing each other in the VR world. First, unlike in the real world, the motion of the passer-by is based on a musculoskeletal model, so it is easy to attract the eyes of the subjects. In addition, visualizing the skeletal makes it difficult to see the eyes of the opponent and to know which direction he is facing and moving to. So, the estimated results of muscle tension did not affect the prediction of the movement of the opponent and the difficulty in predicting the direction of gaze may have affected the subject's walking.

On the other hand, the presentation of environmental information by VisualSLAM does not give the subject a sense of discomfort, but is given as information, and can play a role close to reality in the interaction between the subject, the opponent, and the environment. For sport training, it makes a sense to use the musculoskeletal model. But for reproducing real environment in VR world, it is assumed that using more human-like models is more important. It is assumed that it is more important to use models that do not give the subject a sense of discomfort while keeping the joint positions close to the actual one, rather than using a musculoskeletal model for the presentation of the passing partner, in order to reproduce the passing gait in the VR world, not in sport training.

6 CONCLUSION

The results of musculoskeletal analysis were rendered in VR space, which is useful for ecological training in interpersonal sports. The environmental information was well reproduced, but the general human model was more effective in the walking motion experiment. In the future, it is necessary to reproduce the subject's own information in order to use it for ecological training.

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