Chapter 6

Results

6.1 Introduction

This chapter presents results of both optimization and characterization approaches. In the optimization case, we report results of an experimental study done with persons. We compare data obtained in experiments and those achieved by a simulation environment.

Two case studies demonstrate our system's capability to assess fatigue at joint level and to react when fatigue levels achieve unbearable limits. In the characterization case, the cooperation between the fatigue and the reachability module generates reachable spaces featured with fatigue data.

6.2 Case Studies on Optimization

In the scenario where the optimization takes place, an articulated figure and Inverse Kinematics tasks play a leading role. For example, reaching with the arm certain point in space. Our Inverse Kinematics framework performs this task while allowing the user to interact with the task parameters. A simulation including fatigue calculations begins, when a joint reaches a certain value of fatigue, automatically the mechanism described in section 5.3.1 is launched to search for a less fatigued posture.

The following sections describe the arm and the contraposto case studies. In the arm case, we also describe the experiment where we recorded and analyzed postures adopted by subjects when they felt fatigued.

A performance analysis on a Pentium 1200 MHz with 512 Mb Ram, shows that the computation time is mainly dependent on the number of degrees of freedom of the articulated structure and the number of tasks needed to achieve the goal. In the arm case, the computation time is about 25 seconds. The contraposto case takes about 66 seconds. The computation time includes the time needed to achieve the goal, the time during which fatigue increases until a thresold, the time during which the optimization to minimize fatigue takes place, that is, the recovering and the time to go again to the goal. Figure 6-3 shows a sequence of frames taken from the simulation of the arm case.

6.2.1 Arm Case Study

The arm case study has been applied to an articulated structure for load carrying in the sagital plane. In the following, we describe the experiment and the simulation results.

6.2.1.1 Experiment

The experiment was performed using 12 males and 8 females with ages from 30 to 40 years old. Our purpose was to analyse their behaviour when they had to sustain a load. We wanted to study where and how many positions of recovery they found when they felt fatigued.

The experiment consisted in following a line marked in the wall. The line could be vertical, horizontal or oblique. There is a more detailed description of the experiment in the appendix A of this document.

Making Measurements

We studied the horizontal line, -25 º oblique line and -45º oblique line cases. Several performances of each case were recorded, video were analyzed afterwards.

These were the instructions given to the subjects:

"Stay in the initial position as long as you can. When you feel fatigue, go to a posture where you can find some rest and if you are recovered enough then feel free to move along the line. Experiment stops when you are not able to find recovery along the blue line".

The following graphs depict reached positions during the experiment and how long the subject maintained those positions.

Recordings of the oblique -25º case showed that subjects only found one position of recovery (See Table 6-1). Only one subject found two positions of recovery.

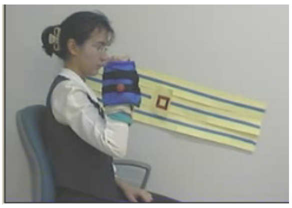
A more complete table, containing more pictures from the experiment, can be found in appendix A.

OBLIQUE (-25º)

Subject 1. Load: 2.5 kg.

Initial posture

Recovery found



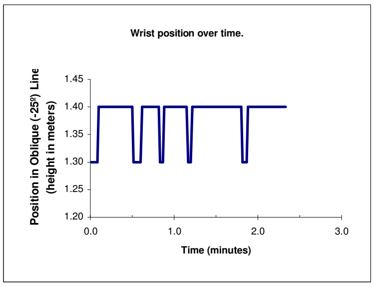


Table 6-1. Experiment on oblique (-25) line

Table 6-2 shows the oblique -45 case in which subjects also found one position of recovery. Although in this case some subjects tried to go downward to get recovery, their feedback was that they did not know why.

One explanation can be found in Berthoz studies. He stated that the mentally simulated action of a contraction lead to the mentally simulated perception of a temporary higher muscle tension required to contract more the biceps at the very beginning of the motion

[Ber96]. That explains why at the beginning of the experiment some subjects chose the opposite direction. However when they realized that the downward movement was even more fatiguing they went upward; this is the direction that minimizes the moment arm and in consequence fatigue.

Another explanation of the subjects' reaction can be found in the well-known muscle length and force relationship (see Figure 6-1). Within the lower half of the muscle length region, a decrease of length produces a diminution of force that requires increasing the muscular tension in order to maintain a constant force. The constant force is needed to maintain static conditions. This feeling of increased tension might drive the subject to feel that the upward direction, where muscle length decreases, was not good to recover.

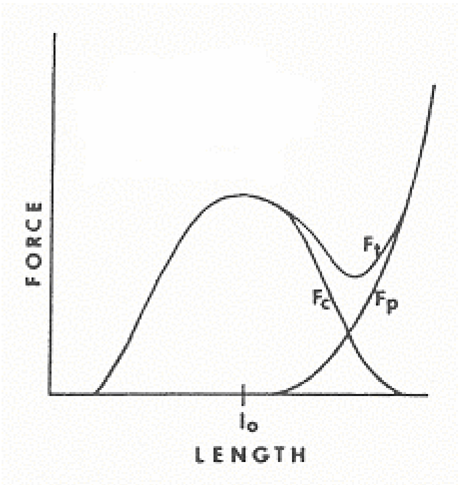


Figure 6-1. Force F_t as function of muscle length, passive F_P and active F_C tension (from [Win90a])

Differences in the timing of postures are normal due to differences in subject's physical conditions. A man sustains a load more time than a woman. Besides, a man that usually does exercise can hold a load more time than the average man.

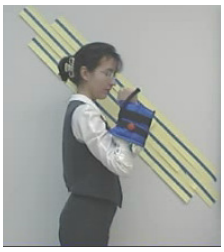
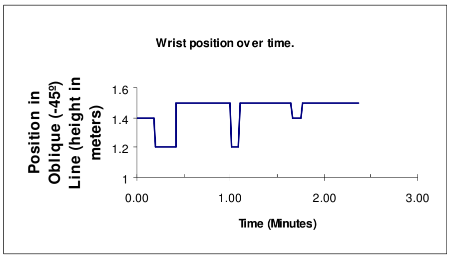
OBLIQUE (-45º)
Subject 1. Load 2.5Kg. Initial posture Recovery found   

Table 6-2. Experiments on oblique (-45) line

Table 6-3 shows the horizontal case. In this case, the conclusion was also that the subjects found only one position to recover from a fatiguing state. Note that the closeness of -25º oblique and horizontal case is reflected in the graphs. Both graphs are rather uniform compared to the -45º oblique case.

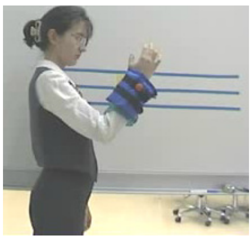
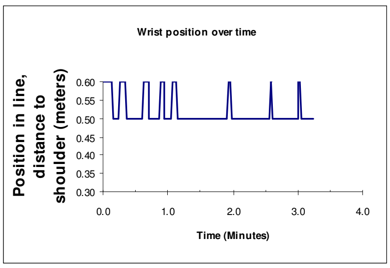
HORIZONTAL
Subject 1. Load 2.5 kg. Initial posture Recovery found   

Table 6-3. Experiments on horizontal line

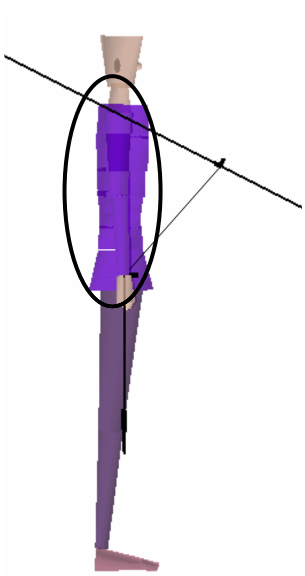
6.2.1.2 Simulation

A simulation environment has been used to validate the fatigue model. The scene includes a virtual arm with shoulder and elbow joints. The arm moves in the sagital plane like the subjects in the experiments.

Figures on Table 6-4 show postures adopted by the virtual arm in different cases. Simulations show the arm reaching a determined value of fatigue and then trying to minimize fatigue value searching for a posture where to find recovery. As the experiments revealed, the simulation found only one position of recovery. When fatigue decreases due to the recovery the arm goes to the initial position and begins again fatiguing, searching for recovering and so on.

Visual information about fatigue at elbow and shoulder joints can be appreciated. Each of them is surrounded by two semicircles representing fatigue of flexor (i.e agonist) and extensor (i.e. antagonist) muscles. The black arrow represents the external load that the arm is lifting.

ARM SIMULATIONS



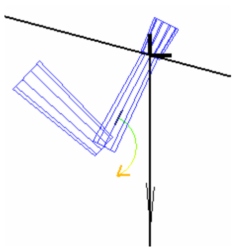
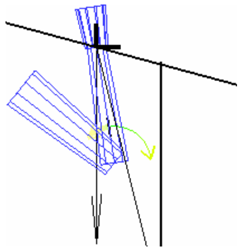
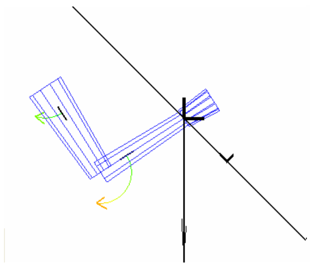
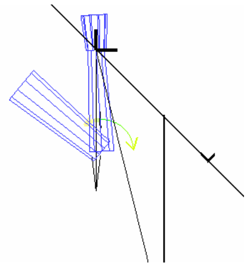
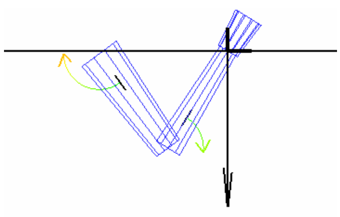
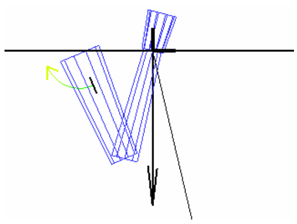
OBLIQUE (-25º)	
Initial posture 	Recovery found 
OBLIQUE (-45º)	
Initial posture 	Recovery found 
HORIZONTAL	
Initial posture 	Recovery Found 

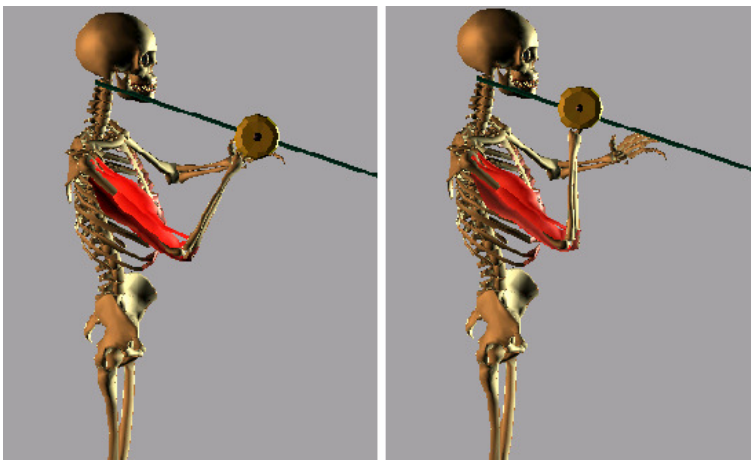
Table 6-4. Simulation results

Despite the computational load of the simulation due to the Inverse Kinematics method, one complementary possibility is to represent muscles as solids and to progressively intensify their color when fatigue increases. Figure 6-2 shows simulation results using a skeleton[1] with colored muscles representing the fatigued group of muscles, in this case, the biceps.

ARM SIMULATIONS using colored muscles

OBLIQUE (-25º)

Initial posture   Recovery found



[1] Designed by Thierry Michellod

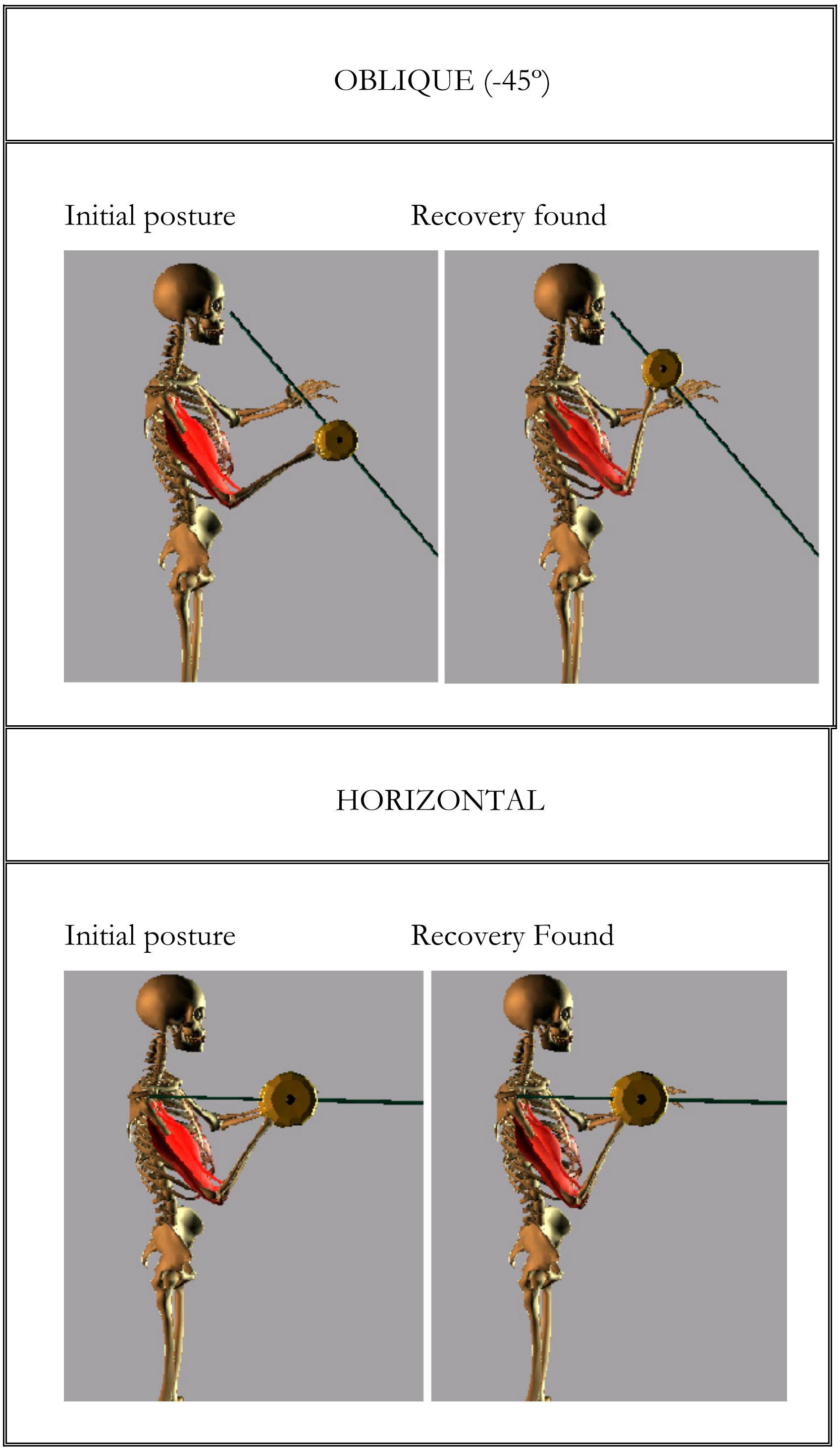
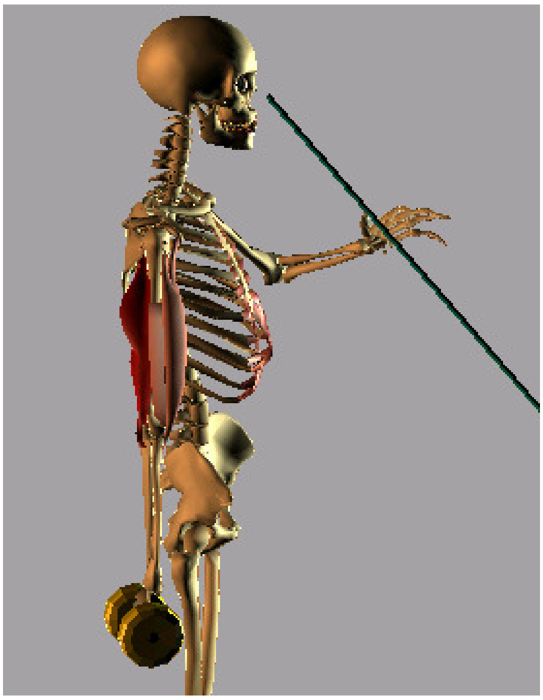


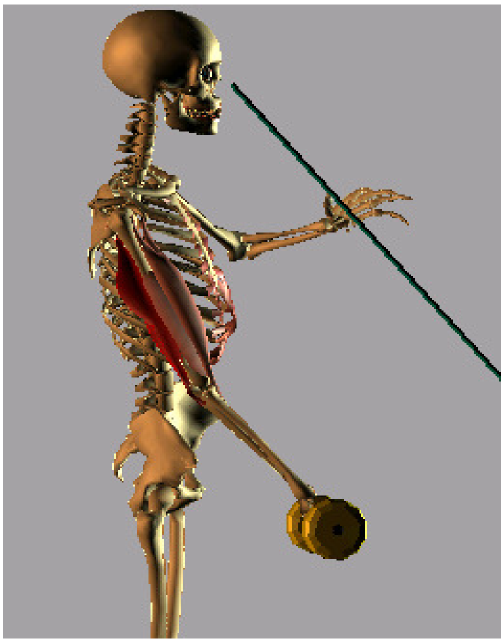
Figure 6-2. Fatigued muscle in red

Figure 6-3 shows a sequence of frames for the oblique -45° case. At the instant of time T0, the virtual human adopts the initial posture. At the instant of time T1, he goes towards the goal situated over the oblique line. At the instant of time T2, the goal is achieved. At time T3, the subject maintains the posture and a significative value of fatigue is reached. It is appreciated by the intense red color in the bicep muscle. Fatigue increases even more until instant of time T4. At the instant of time T5 when fatigue reaches certain threshold, the posture is adjusted in order to minimize fatigue. At time T6, it is achieved a posture where recovery is found, then fatigue decreases. It is appreciated in the less intensive red color in the muscle. Once revovered, from instant of time T7 to T8 the arm goes towards the goal again.

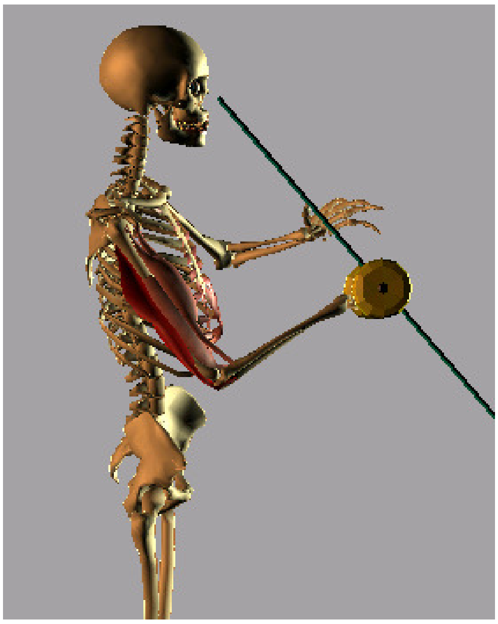
Instant of time T0: Initial posture



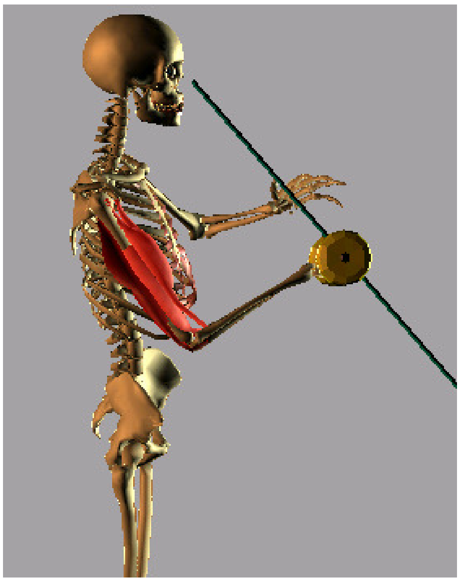
Instant of time T1: Go towards the goal



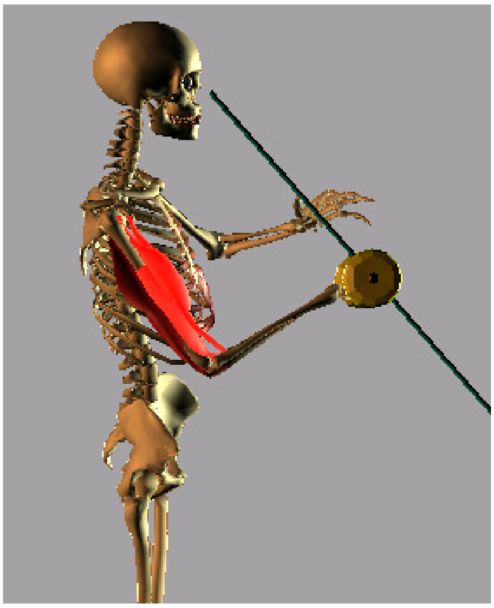
Instant of time T2: Goal reached



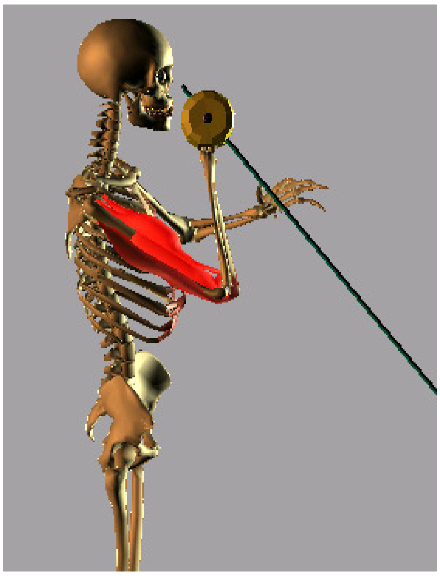
Instant of time T3: Maintaining the posture, then a significative value of fatigue is reached (red color in bicep muscle)



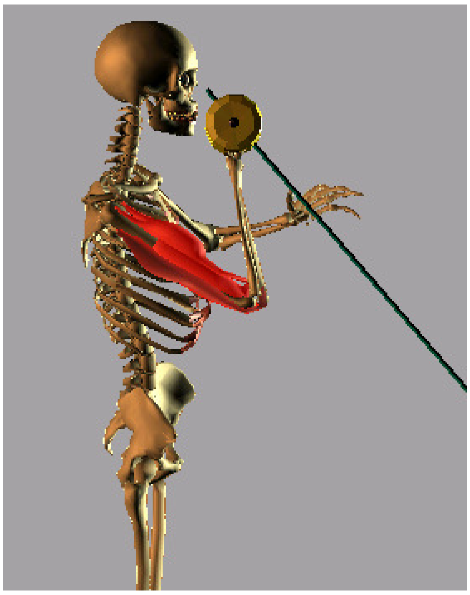
Instant of time T4: Fatigue increases even more



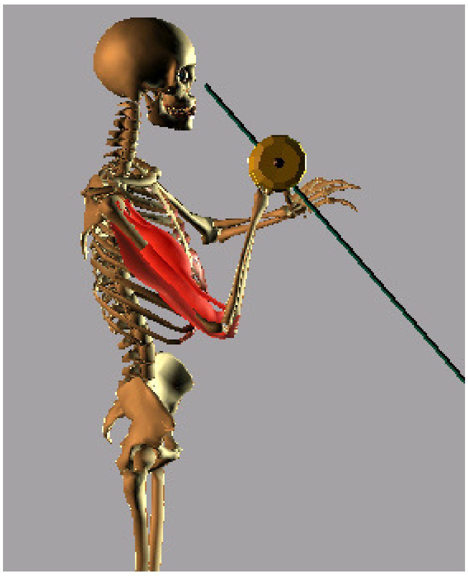
Instant of time T5: When fatigue reaches a threshold, posture is adapted to minimize fatigue



Instant of time T6: Recovery is found, then fatigue decreases (less intensive the red color in muscle)



Instant of time T7: Once recovered, go again towards the goal



Instant of time T8: Go towards the goal

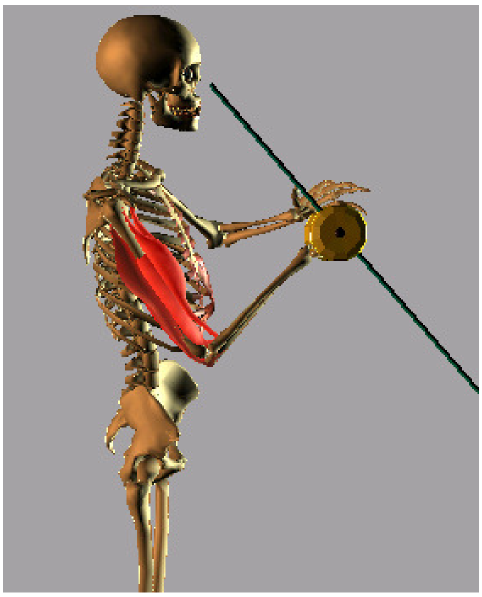


Figure 6-3. Oblique -45° case: sequence of frames

6.2.2 Contraposto Case Study

The contraposto case study analyses the postures adopted by humans when they are standing. If the act of static standing were continuously stationary, body supporting tissues would be subjected to uninterrupted stress. Postural fixity produces restriction in blood flow, which can cause body discomfort [San92].

However, if the act of standing is a continuous alternation of symmetrical poses, the continuity of the stress affecting the tissues would be broken, but the stress would still affect the same tissues in each successive attitude, and the period of rest would be short [Smi53].

Alternating between the two asymmetrical postures (see Figure 6-4), the period of rest is extended. Thus in one asymmetrical pose (e.g. asymmetrical left), stresses act along the left side of the body and the right side is almost released of any load. When the weight is shifted on to the right foot, that is, when asymmetrical right posture is adopted, the distribution of stress is completely altered. Those parts which were compressed are now rested or subjected to tensile stress and viceversa. Studies on asymmetrical poses have stated that the average duration of asymmetrical postures is approximately 30 (+/-20) seconds.

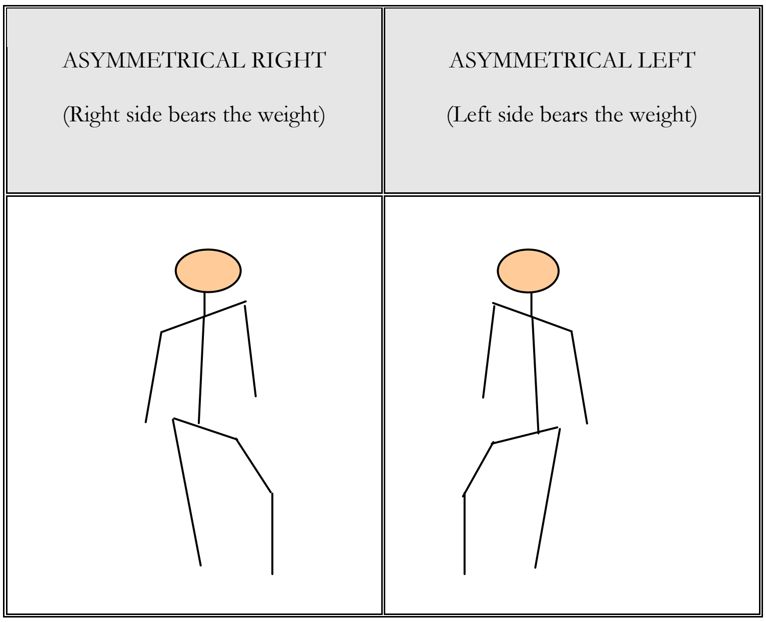


Figure 6-4. Alternation between asymmetrical postures

6.2.2.1 Joints Involved in an Asymmetrical Posture

Evans made an extensive study of the joints and ligaments involved in an asymmetrical posture This posture is also called the "pelvic slouch" [Eva79]. In the case in which the right leg supports the weight (see Figure 6-5), the affected joints are the right knee and the right hip. The bearing knee goes into full extension. Then, passive joint torque reaches a significative value. It is defined as the moment acting when all muscles crossing the joint are relaxed. The passive joint moment arises from the deformation of all tissues which surround the joint including skin, ligaments, etc.

The bearing side of the pelvis, the right hip joint, lifts until it hangs on the iliotibial tract. The iliotibial tract is a ligament of great strength and some elasticity which carries the body weight in adduction. It resists adduction, that is, produces an abductor torque. Ligaments are strong bundles of fibers that stabilize the joint, guide joint motion and prevent excessive motion.

As conclusion, in an asymmetrical stance, the knee of the supporting limb is fully extended and the thigh fully adducted, therefore knee and hip joints finish up hanging on their ligaments which produce passive moment.

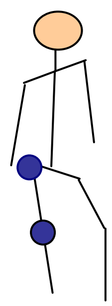


Figure 6-5. Joints involved in an asymmetrical right pose

6.2.2.2 Simulation

To create the contraposto posture, we set several tasks. Firstly, one of the feet is selected as main support, then the center of mass is directed towards that foot. An orientation task is set in a cervical joint; the objective is to achieve an erected posture. The root of motion is situated in the bearing foot, and a position task is situated in the left foot.

Once the simulation containing the set of task described above starts, the virtual human adopts a posture where all of them are achieved. As described in section 5.3.1, when a joint, in this case the right hip, overcomes a threshold value of fatigue, a mechanism is launched to diminish it.

Figure 6-6 shows the result of simulations applying the fatigue model and minimization described in chapter 5. The black line indicates that the center of mass is being controlled. It is projected over the supporting foot.

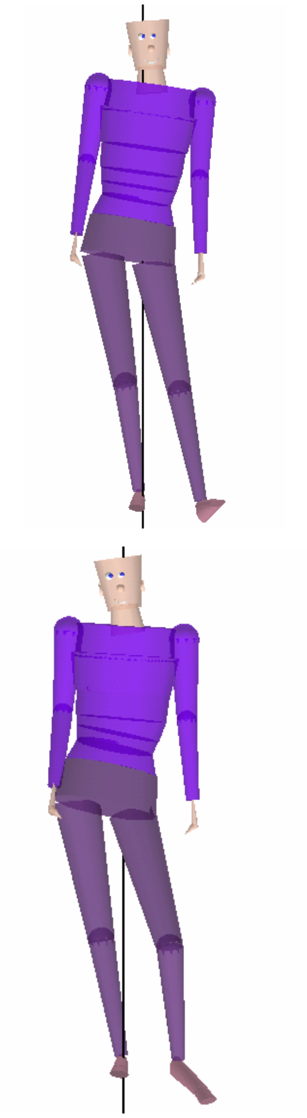


Figure 6-6. Standing posture of the virtual human

Figure 6-7 shows the David of Michelangelo. This sculpture adopts the contraposto posture. It is drawn the line of balance passing though the supporting leg, hip abduction and knee joints. Note how the pelvis falls towards the relaxed leg.

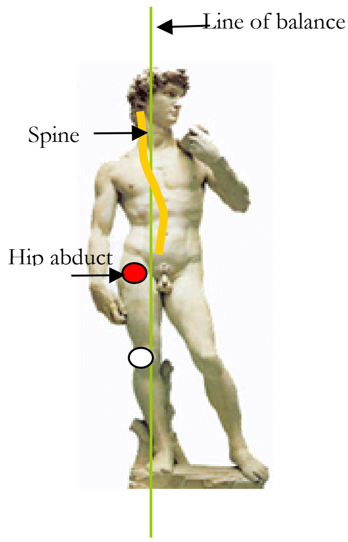


Figure 6-7. Art creation adopting standing posture

In the Appendix B several pictures can be found where contraposto is adopted by art creations.

6.3 Simulation Environment

A User Interface (UI) has been developed to provide real-time guidance of fatigue in order to provide insight into its evolution. The interface also allows the interactive manipulation of articulated figures using the Inverse Kinematics technique. It is possible to edit data about joints or solid nodes belonging to the loaded structure. It is also possible to edit the parameters of position, orientation or center of mass tasks (See Figure 6-8).

In this environment, we can work either with *normal* joints *or half-joints*. External loads can be applied to any body members. Body weight can also be set and visualized.

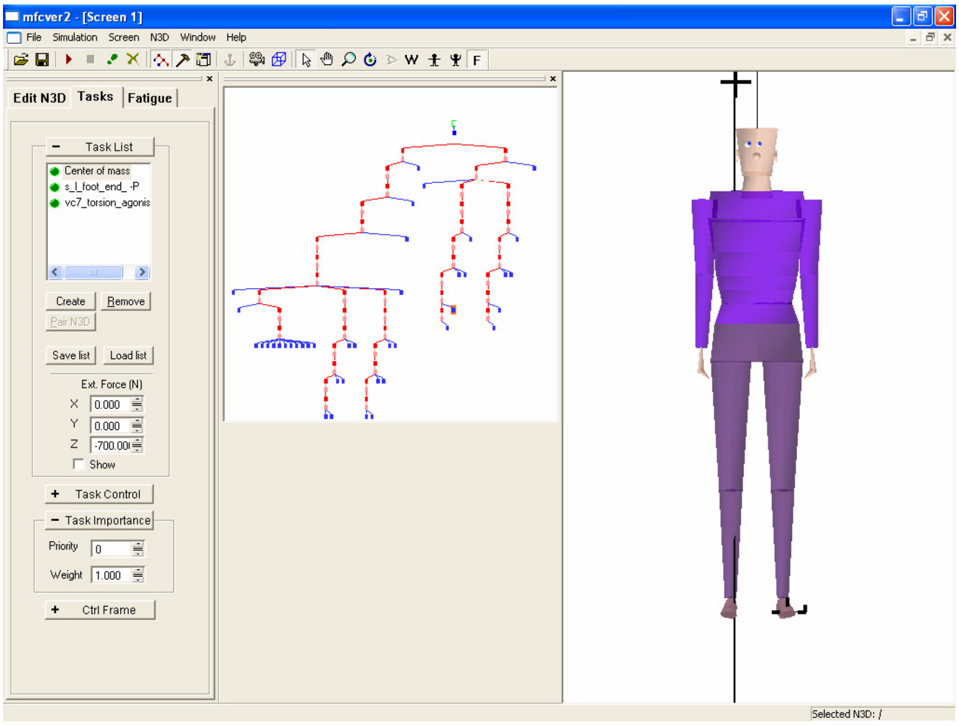


Figure 6-8. Simulation environment

In Figure 6-9, visual information about fatigue at elbow and shoulder joints can be appreciated [Rod03a]. Each of them is surrounded by two semicircles representing fatigue of flexor and extensor muscles. Black arrow represents the external load the arm is lifting. The line crossing the body indicates that the center of mass is being controlled.

The main advantage of our approach is that we get a good real time perception of how fatigue evolves in different muscle groups. Otherwise using curves to show fatigue over time, it would be really difficult to follow fatigue evolution.

In the case where the arm moves in the vertical plane, we have only two half-joints. How could we follow the fatigue evolution of many of them in the case of all the body joints? Curves are a good tool to analyze data but not during an ongoing simulation. Another advantage of our approach is that we see fatigue information just on the site where it is produced; it gives us a good feedback of what parts of the human are more fatigued at each time step. The user can save a file with extension .ik where data about Inverse Kinematics tasks are stored.

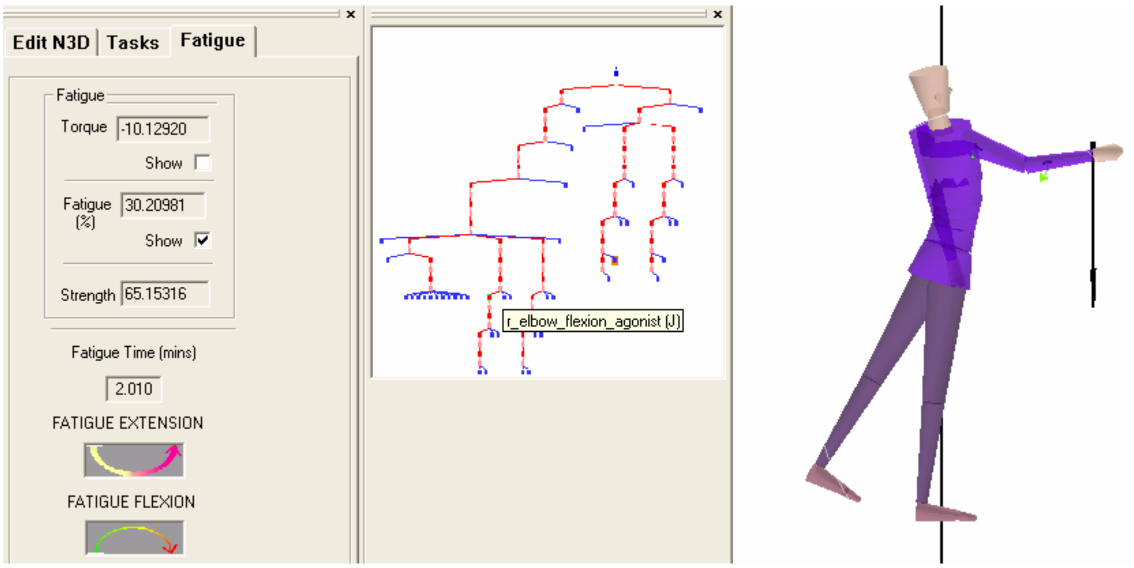


Figure 6-9. Visual data about fatigue

6.4 Fatigue and Reachability Framework

A human posture can be mainly characterized by the joint angles needed to adopt the pose. Another feature that can be useful to characterize a pose is the fatigue values arising with that posture.

In the framework where the fatigue characterization takes place, we find three main elements: a virtual human, a reachability space and fatigue conditions (see Figure 6-10) [Rod03e].

The virtual human performs a reach task. It is possible to select which hand/feet will perform the reach.

The reachability space is defined by an initial box whose dimensions and position in space can be set interactively (see Figure 6-11). Reachability volume is generated as explained in section 5.4.1. Fatigue conditions are defined by the external load that will be sustained by the virtual human. It is also possible to establish how long fatigue calculations will take.

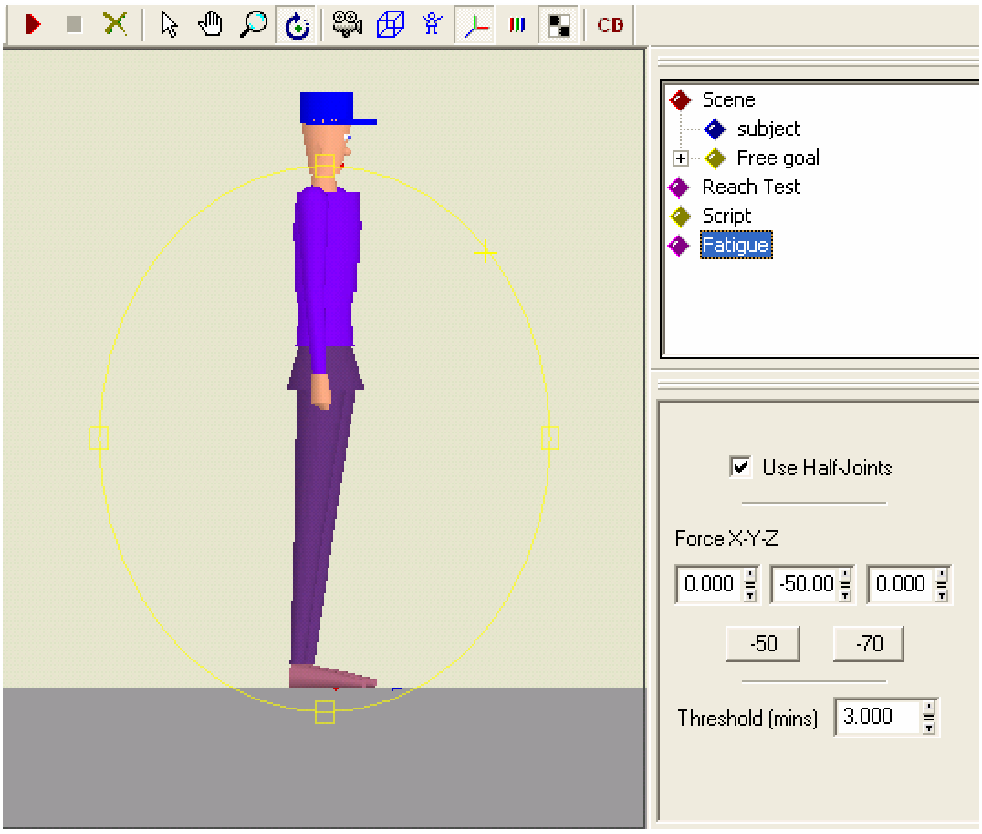


Figure 6-10. Fatigue & Reachability framework

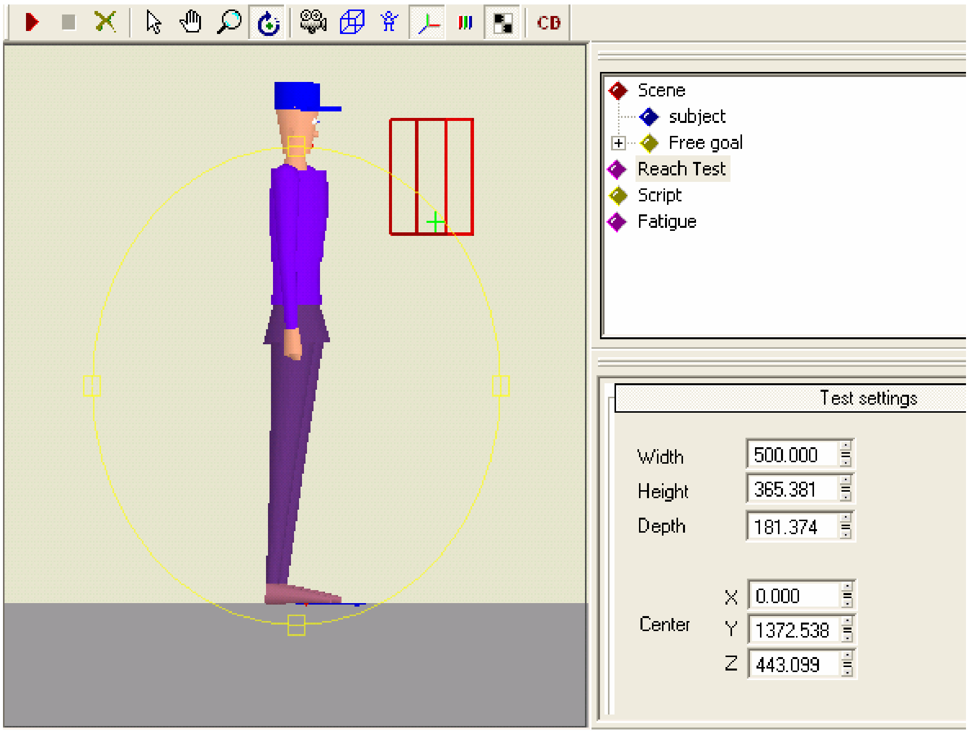


Figure 6-11. Initial box

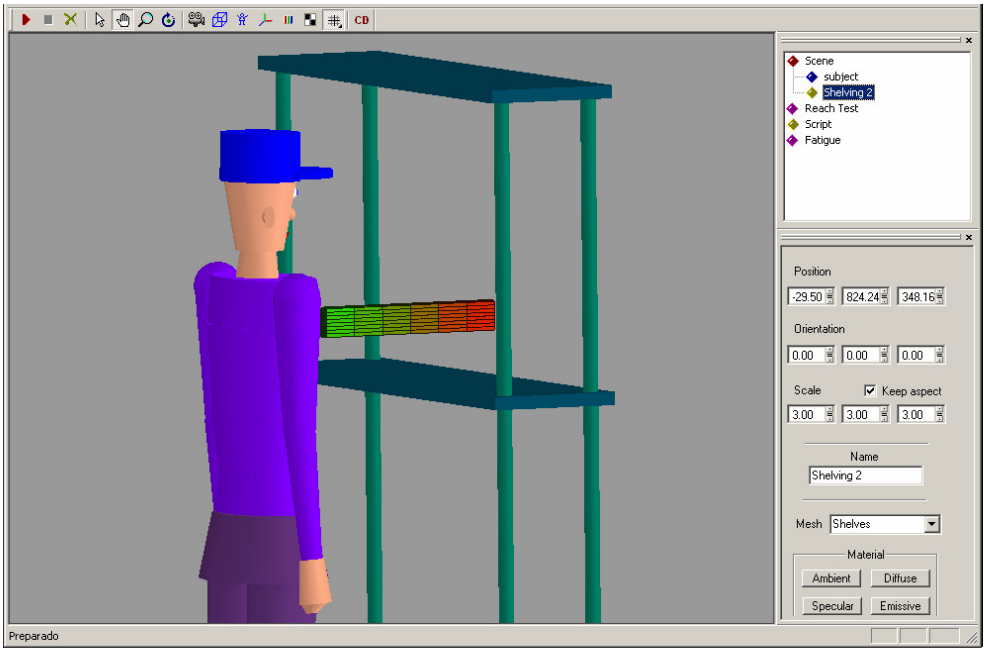


Figure 6-12. Reachable box with fatigue data

For each point in the reachability space, beside the reachability/unreachability conditions, we store fatigue values. Then, it is possible to characterize the reachable space using fatigue data. A pure green color indicates a low value of fatigue. A gradual red color appears when fatigue values begin to be higher. A pure red color indicates a high fatigue value. As can seen in Figure 6-12 green color in the reachable area near to the body indicates less fatigue than the mixture (green-red) color found in farther positions.

6.5 Summary

In this chapter, we describe two approaches of fatigue applicability. The first one exploits fatigue with the objective of posture optimization and in the second one fatigue is exploited for postures and reachable space characterization.

In the optimization approach, the arm and the contraposto cases are analyzed. Both of them use fatigue data given by the fatigue module in order to achieve a less fatigued posture. We compare results from experiments and the simulation environment.

In the characterization approach, the reachable space by the human arm is featured with the fatigue factor. Then, the posture adopted to reach every point in that space is also characterized by fatigue data. A simulation environment provides visual data about fatigue and reachability.