SIMULATION OF LIFTING USING THE BETTER OF TWO WORLDS: FORWARD AND INVERSE DYNAMICS

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Abstract. The aim of this study was to use an inverse dynamic analysis to calculate a starting point for a forward dynamic simulation in order to decrease the calculation time.

Two identical 2-D musculo-skeletal models of the leg and upper-body were built in SIMM and AnyBody consisting of 7 rigid segments connected with hinge joints. The model was equipped with 15 muscle units. Three simulations were performed: (1) A forward dynamics tracking optimisation with SIMM where the starting guess was randomised and three optimisations were performed, (2) an inverse dynamics analysis with AnyBody using a video analysed lift as input and (3) The calculated muscle activations of step 2 were used as a starting guess for a new tracking optimisation with SIMM.

The time consumed in the optimisations with random initial guesses were between 27 h 48 min and 36 h 56 min. Using the results from the inverse dynamics optimisation as the starting guess, the time consumed was 12 h 28 min.

Using an inverse dynamics approach to determine the muscle activities for the starting guess caused the optimisation time in the forward dynamics analysis to be less than half as long. With complicated models it seems appropriate to use an inverse dynamics approach to find a suitable starting guess. This will make forward simulations of sudden spine loading realistic with more detailed models.

1. Introduction

Sudden loading of the spine is believed to contribute to the development of low back disorders (Magnusson *et al.*, 1996). When a sudden load is applied to the upper body, the muscles surrounding the spine will contract to maintain balance, often with large forces (Mannion et al. 2000). Contracting the muscles around the spine will lead to a rise in the compression force along the spine. Furthermore, the flexion or extension of the spine, caused by the load, will lead to a non-optimal placement of the spinal segments in relation to each other (Cholewicki and McGill, 1996). A combination of flexion/extension and a large compression increases the risk of developing low back pain (Adams and Hutton, 1982; Bernard, 1997). Studies on the reactions to sudden loading have been simple with regards to force application and possible movements. Furthermore, studies on human subjects are restricted in terms of the size of the force applied to avoid injury.

In order to quantify sudden loading of the spine (similar to those in real-life situations), Andersen (2001) made a forward dynamics simulation of sudden loading during a dynamic lifting task using SIMM (www.musculographics.com). Due to the long calculation times, however, it was necessary to use a simplified model of the spine with only one muscle. In order to be able to use a more realistic model including several muscles, the calculation times has to be decreased. It is possible to calculate individual muscle activations by an inverse dynamics analysis using the software AnyBody (www.anybodytech.com). These calculated muscle activations might then decrease the calculation times if used as an estimated starting point for the forward dynamic simulations.

The aim of this study was to use an inverse dynamic analysis to calculate a starting point for a forward dynamic simulation in order to decrease the calculation time.

2. Methods

Two identical 2-D musculo-skeletal models of the leg and upper-body were built in SIMM and AnyBody consisting of 7 rigid segments connected with hinge joints (Figure 1).

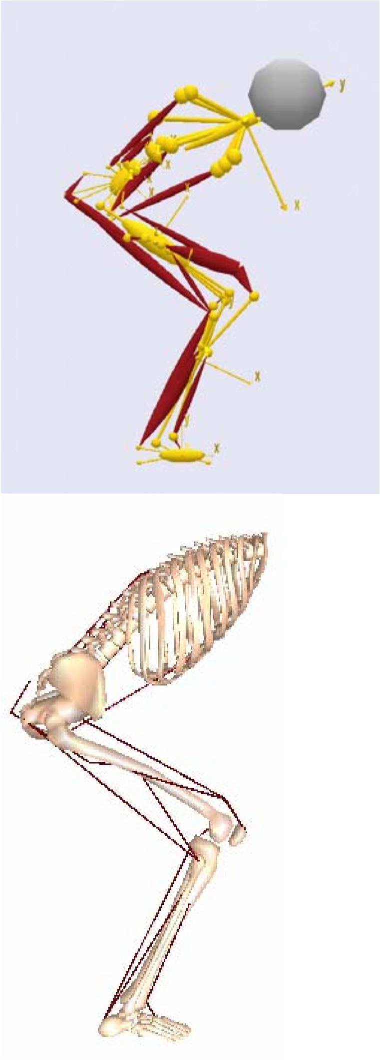

Figure 1 The two identical lifting models with different graphical representations. Top: AnyBody, Bottom: SIMM.

The segments represent a foot, shank, thigh, pelvis, the fifth and fourth vertebra as one segment, the third and second vertebra as one segment, and a thorax segment. The model was equipped with 15 muscle units, which reflect the actions of erector spinae, multifidi, iliopsoas, rectus abdominis, hamstrings, gluteus maximus, rectus femoris, vasti, gastrocnemius, soleus, and tibialis anterior. In this study a simplified muscle model was used, where the maximum muscle strength is independent of muscle length and shortening velocity. The basis for the simulations was a video-analysed (200 Hz) fast lifting movement of a 20 kg mass.

Three simulations were performed:

1. A forward dynamics tracking optimisation with SIMM using the Bremermann algorithm followed by a simplex algorithm. The starting guess was randomised and three optimisations were performed. The activation of each muscle was described by the starting activity and two coordinate sets of time versus activity. To each of these "square" functions, a spline function was fitted, which was input to each simulation. Hence, with 15 muscles, the optimisation space was 75 dimensional.
2. An inverse dynamics analysis with AnyBody using the video analysed lift as input. The outputs of this analysis were individual muscle activations and forces. AnyBody implements a min-max objective function for the solution of the muscle recruitment problem. This objective function is equivalent to allowing the power to which the sum of muscle stresses is raised in previously reported polynomial objective functions to approach infinity (Rasmussen et al. 2001). For a detailed description of the AnyBody Modeling System we would like to refer to the paper by Rasmussen et al. (2003), which will also be presented at this symposium.
3. The calculated muscle activations of step 2 were used as a starting guess for a new tracking optimisation with SIMM.

The 3 simulations were all performed on the same computer (Intel Pentium IV processor, 1.4 GHz, Win2000). The output and the calculation times were compared with each other.

3. Results

The time consumed in the optimisations with random initial guesses were between 27 h 48 min and 36 h 56 min. Using the results from the inverse dynamics optimisation as the starting guess, the time consumed was 12 h 28 min. The same optimum was found in all optimisations except one (which found a local minimum). The mean difference between the human and the simulated movement was 1.47 degrees at each joint.

Figure 2 shows a comparison of the joint angles in the optimised and the video-recorded movement. It can be observed that the two movements are similar. However, the optimised movement exhibits large accelerations when the joints exceed their range of motion.

As figure 3 shows, the compression forces calculated through the inverse dynamics method was larger than usually seen in lifting motions. The video-analysed motion, however was very fast (<0.35 s) which causes large accelerations, yielding large forces.

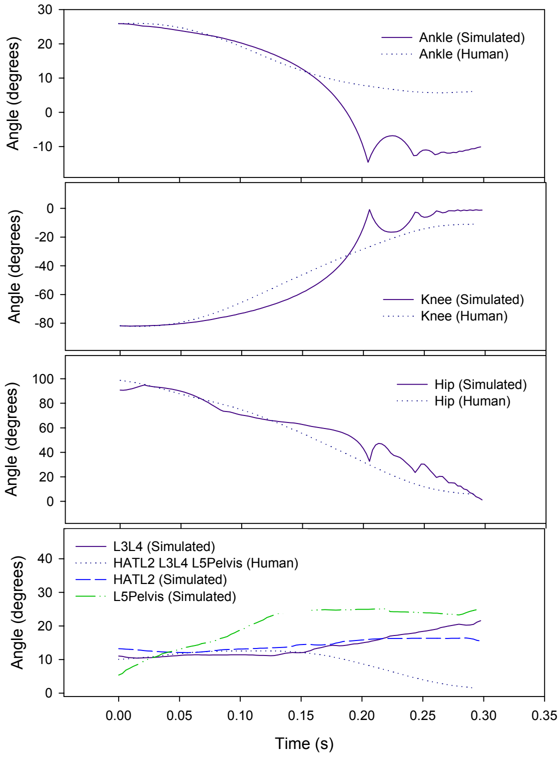

Figure 2 Comparison of the movements of the joints during the simulated and the video-analysed lifting motion.

4. Discussion

The Bremermann method to optimise a set of input parameters searches in a random direction. To find an optimum in this manner is time consuming but allows the optimisation algorithm to continue even if it finds a local optimum. Using an inverse dynamics method to estimate an optimal set of muscle activities, and using these as input to the forward dynamics optimisation saved 50% of the optimisation time. However, this demands that the models created in both systems are identical.

The forward dynamics optimisation requires that the muscle excitation patterns are simple. In this study, only 5 variables described the muscle excitation. Accordingly, it was not surprising that the optimised movement did not track the human movements very closely.

Thelen et al. (2003) presented a method called computed muscle control in order to decrease calculation times of dynamic optimisations. Their approach was to integrate inverse dynamics and forward dynamics in one muscle control algorithm. They were able to find a solution in 10 minutes for a pedalling simulation with a model equipped with 30 muscle units with 1.7 GHz Pentium IV.

Our approach was to simply use an inverse solution as a starting guess for the forward dynamics optimisations, which decreased the calculations times already with more than 50 %. It would be interesting to see if Thelen's algorithm would work as well on the lifting problem (a non-cyclic movement) as on the pedalling problem (a cyclic movement).

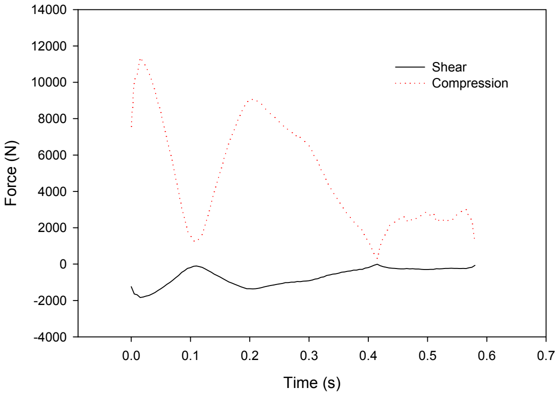

Figure 3 Compression and shear forces at the L5 level.

5. Conclusions

Using an inverse dynamics approach to determine the muscle activities for the starting guess caused the optimisation time in the forward dynamics analysis to be less than half as long. With complicated models it seems appropriate to use an inverse dynamics approach to find a suitable starting guess. This will make forward simulations of sudden spine loading realistic with more detailed models.

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