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ABSTRACT

This paper investigates the significance of including support points in musculoskeletal models to assess manual operations, specifically mounting operations such as in vehicle assembly lines. The typical situation is a worker leaning over a vehicle to mount a hose with one hand while supporting the body with the other hand or other body parts on the vehicle body. This creates several closed chains in the resulting mechanism and disables computation of reaction forces by equilibrium alone. The paper shows how muscle recruitment algorithms typically used in musculoskeletal models can alleviate this problem. The paper concludes that, to assess these situations, digital manikins could benefit significantly from the advanced simulation algorithms typically embedded in musculoskeletal systems.

Keywords: Musculoskeletal, biomechanics, digital manikin, ergonomics, assembly line, mounting.

INTRODUCTION

Digital manikins are software tools originally developed to assess the kinematic and sizing compatibility between humans and environments. In recent years, several manikin tools have also been equipped with kinetic capabilities for assessment of strength in different postures, joint moment, compliance with health and safety regulations etc. These analyses are based on fundamental principles of equilibrium of open chains and are typically not capable of handling cases with multiple support points, for instance by the hands as well as the feet. In other words, the digital manikin development is characterized by models that are simplistic from a biomechanical point-of-view but very operational from a user perspective.

In parallel with this development, a number of software tools for much more detailed musculoskeletal analysis have grown out of the biomechanics scientific community. Some of these tools, for instance the AnyBody Modeling System (Damsgaard et al, 2006) contain detailed muscle configurations and are capable of handling closed kinematic chains and statically indeterminate situations in which all the unknown forces in the system, including the forces exchanged with the environment through boundary conditions, are estimated computationally. In many cases, this allows for complete *in-silico* ergonomic investigations in the sense that the posture or motions in the problem are mostly given by the kinematic connection with the environment and the forces acting on the system are determined from equilibrium and muscle recruitment alone and do not require measurement of support forces and the like by force platforms and dynamometers.

The musculoskeletal modeling tools are characterized a high degree of accuracy and complexity, but they are also technical and not as accessible to users as digital manikins. This sparks the idea of hybrid models in which the user interfaces of digital manikins are equipped with the sophisticated biomechanical analysis methods of musculoskeletal models.

In this paper we study the added value of musculoskeletal models in ergonomic investigations and make the case that putting these models “inside” digital manikins may significantly enhance the applicability of both technologies for ergonomic design, occupational health and other important fields.

MUSCULOSKELETAL SIMULATION METHODS

Methods for musculoskeletal modeling are traditionally separated into the two complimentary approaches of forward an inverse dynamics. In forward dynamics, presumed muscle activations create muscle forces and cause movements of the skeleton. Reproduction of real motions then requires the knowledge of which muscle activations created the motion. This knowledge can be derived from either experimental results or by solution of optimum control problems that are computationally very costly. For examples of forward dynamics simulations, please refer to Neptune and Hull (1998), Spagele et al. (1999) and van Dieen et al. (2003).

In inverse dynamics, the desired motion is input to the computation and the algorithms compute backwards to the muscle forces and subsequently to muscle active states that created the movement (Erdemir et al., 2006). This approach is more tractable for ergonomics-type of investigations because movements are easy to observe and in many cases are given by the environment constraints.

Recent years have seen the advent of composite methods (Thelen et al., 2003, Andersen at al., 2011) that combine the best features of forward and inverse dynamics. However, in the following section and in the example of the next chapter, we shall review the potential of pure inverse dynamics in more detail as an engine for biomechanically founded ergonomic investigations in the realm of digital manikins.

THE ANYBODY MODELING SYSTEM

The AnyBody Modeling System is computer software designed for constructing complex models of the human body and for determining the environment's influence on the body. The mathematical and mechanical methods of the system were described in detail by Damsgaard et al. (2006). The system is based on inverse dynamics and presumes that muscles are recruited according to a minimum fatigue criterion and is capable of simulating the force in every muscle and reactions in every joint and external support condition for prescribed movements and external loads.

The model is sized roughly as a 50th percentile European male. The model is scalable with population percentiles as well as on individual levels, but the anthropometrical influence is beyond the scope of this work.

MUSCLE RECRUITMENT

This model comprises approximately 1000 individually activated muscles, causing a mechanical situation of vast statical indeterminacy in the sense that the number of muscles much exceeds the number of degrees of freedom of the system. Muscle recruitment is therefore accomplished with an optimality criterion presuming that the muscles are recruited by the central nervous system to minimize some physiological criterion (Rasmussen et al., 2001):

Minimize $$G(\mathbf{f}^{(\mathrm{M})}) \tag{1}$$

Subject to $$\mathbf{Cf} = \mathbf{d} \tag{2}$$

$$f_i^{(\mathrm{M})} \geq 0, \qquad i \in \{1, \ldots, n^{(\mathrm{M})}\} \tag{3}$$

where **f** is the vector of $n^{(\mathrm{M})}$ unknown muscle forces, $\mathbf{f}^{(\mathrm{M})}$, and joint reactions, $\mathbf{f}^{(\mathrm{R})}$. **C** is the coefficient matrix, and **d** is the right hand side comprised by external forces, inertia forces, and passive elasticity in the tissues of the body. Several suggestions for the objective function *G* can be found in the literature (Erdemir et al., 2006). Reasonable criteria are functions of the normalized muscle forces, $f^{(\mathrm{M})}_{\mathrm{i}}/N_{\mathrm{i}}$, where N_{i} is some measure of the muscle strength at each muscle's current working conditions. Rasmussen et al. (2001) demonstrated that many of the criteria are asymptotically equivalent to a minimum fatigue criterion, a min/max criterion:

$$G(\mathbf{f}^{(\mathrm{M})}) = \max\left(\frac{f_i^{(\mathrm{M})}}{N_i}\right) \tag{4}$$

The problem can be converted to a linear form via the so-called bound formulation. This leads to a linear programming problem with muscle forces and joint reactions as free variables, and it can be solved by a variety of algorithms including Simplex and interior point methods.

The min/max formulation of the muscle recruitment problem causes muscle activations to form groups at different activity levels. In particular, the top level, i.e. the level formed by the muscles with maximum activity at a particular time step, is usually shared by multiple muscles. This behavior is a consequence of the criterion, which causes maximum muscle synergism; other muscles come to the aid of highly loaded muscles and many muscles will share the same activity level and contribute to carrying the load corresponding to their individual strengths.

The maximum muscle activity is also called the "activity envelope". The convexity of the reformulated min/max criterion guarantees that there is no other muscle recruitment strategy that can lead to a lower envelope, and it is therefore effectively a minimum fatigue or minimum effort criterion. Thus, the envelope directly reflects the perceived muscle fatigue and therefore is a convenient measure for evaluation of a given task's potential for fatiguing the body.

KINEMATICS

The equilibrium equations (2) in the muscle recruitment problem (1)-(3) comprise posture information and velocity-dependent forces, i.e. centrifugal forces, gyroscopic forces, and Coriolis forces, which require the posture and motion of the model to be known prior to solution of the kinetic problem. For any mechanism that is not very simple, this kinematic analysis is a complex matter requiring extensive coordinate transformations of vectors and matrices in three-dimensional space. This analysis is particularly challenging because closed chains are inherent in the human body and in the situations we may wish to analyze, including the mounting example of the next chapter.

In the AnyBody Modeling System, a so-called Cartesian method (Nikravesh, 1988) relying on a general set of nonlinear, implicit equations, is used to solve the kinematics:

$$\mathbf{\Phi}(\mathbf{q}, t) = \mathbf{0} \tag{5}$$

where $\mathbf{q}$ are the system coordinates comprised of locations and rotations of all the segments in the system, t is time, and $\mathbf{\Phi} = \mathbf{0}$ is the system of all kinematic constraints in the system, typically joints and motion drivers, regardless of the system topology. The consequence of this approach is that there is no distinction between open or closed chain kinematics. This implicit formulation provides the maximum amount of generality allowing for any topological configuration of the system at the cost of computational efficiency owing to the fact that Eqs. (5) are generally nonlinear. It turns out, however, that the kinematic analysis is rarely the bottleneck of the computations.

As nonlinear equations, (5) may have a single solution, multiple solutions or no solution at all, even in the case where the number of equations matches the number of system coordinates. Cases of no solution arise when impossible kinematic constraints are imposed, for instance requiring the hand to reach a point beyond the length of the arm. However, a more common cause for empty solution sets is the presence of more constraint equations than system coordinates, and this is a frequent occurrence when driving the model with motion capture data. The remedy is to make use of solvers that minimize the right hand side of (5) without requiring complete fulfilment of the equations, and this actually leads to opportunities to exploit the redundancy of equations to determine unknown system parameters, such as functional joint locations or joint axis orientations and described by Andersen et al. (2010).

MUSCULOSKELETAL MODELS VERSUS MANIKINS

It is important to notice that the kinetic and kinematic methods described in the previous two sections are fundamentally different from the modeling approaches of most digital manikin systems. Digital manikins are interactive tools in which the computational efficiency must be good enough to allow the user to manipulate the model in real time on the screen, and the methods described in the two preceding sections are not quite efficient enough to allow that. On the other hand, efficient open chain kinematics will not allow for the modeling of multiple support points. Finally the level of detail of realistic muscle configurations are much beyond the anatomical resolution that an interactive tool is capable of.

In the following section we use the example of a mounting operation to demonstrate the importance of biomechanical fidelity in the models, the handling of statically indeterminate situations and the importance of closed chain kinematics.

APPLICATION EXAMPLE: MOUNTING OF A HOSE

In the following, we shall discuss a well-known application example. The case is an assembly line worker mounting a hose in the engine compartment of a car. The working posture is standing, bent over the front of the car, reaching into the engine compartment and applying a force of 120 N with the right hand in the body’s medial direction to force the hose over a nozzle. It is presumed that the hose is over the nozzle such that it can support forces normal to the movement of the hose to some extent, should this be advantageous for the worker. The worker furthermore has a support point for the left hand available on the edge of the engine compartment. The model is illustrated in Figure 1.

Please notice that, due to the nature of the muscle recruitment problem (1) – (3), the body will only exploit these options for support if they are beneficial in terms of muscle recruitment, i.e. if the supports are not beneficial, the algorithm will predict that no force is transferred over them. This is a consequence of the algorithm’s ability to resolve statically indeterminate situations, i.e. more support points than strictly necessary, according to the muscular strengths of the different body parts in different directions.

RESULTS

The model predicts a maximum muscle activation of 49% of maximum voluntary contraction (MVC) to perform the mounting operation when the left hand support is used. Figure 1 provides a visual impression of the muscle recruitment pattern. The muscle coloring reveals that the higher relative muscle activations are found in the thoracic and shoulder regions and that the muscle loads in the spine and in the two legs are rather asymmetrical despite the support of the left hand, which is transferring a total force of 131 N to the car body.

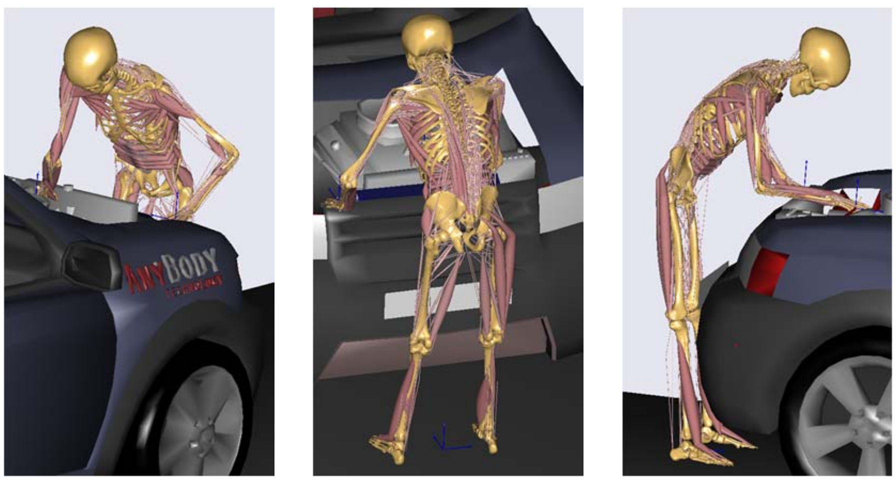

FIGURE 1. The mounting model. The right hand applies a load of 120 N in the medial direction. The left hand is supported on the edge of the engine compartment. Muscle thicknesses are proportional to the forces and muscle redness is proportional to muscle active state.

We subsequently disable the support of the left hand. This drastically changes the muscle activation of the entire body and requires a maximum muscle activation of 112%, i.e. beyond the strength of the model.

The support conditions also significantly influence the joint loads. Table 1 summarizes the results for the two simulated cases.

Table 1. Summary of results of the three analyzed cases. Left and right GH are the total gleno-humeral joint forces in the left and right shoulders respectively. L4/L5 refers to the lumbar vertebral joint between L4 and L5, and the left hand force is the support force between the left hand and the car body.

	Left hand support	**No left hand support**
Muscle activity	49%	112%
Right GH force	1640N	2295 N
Left GH force	1278 N	621 N
L4/L5 force	1026 N	2629 N
Left hand force	131 N	0 N

DISCUSSION AND CONCLUSIONS

It is not surprising that the left hand support condition changes the result of the simulation completely. It is obvious from simple equilibrium considerations that no simulation model disregarding this additional support can provide reliable information about the body loads following from the mounting operation in question.

It is more surprising, however, that the gleno-humeral joint force in the right elbow is influenced significantly by the support conditions of the left hand. According to Newton's third law the force applied by the right hand to the hose is reflected oppositely on that hand and causes moments in the joints from the wrist through the elbow and shoulder and further down the body. The gleno-humeral joint from this point-of-view appears to be part of an open chain, which is statically determinate and should not be influenced by the support conditions of the left hand.

However, the entire model comprises several closed chains of which the right arm partakes. One is closed through the nozzle and the car body through the ground to the feet. Another is between the right and the left arm through the car body. Finally, the human body itself contains much overlooked closed chains, for instance in the forearm because it contains the two bones radius and ulna connected at the elbow and wrist and enabling pronation and supination and in the shoulder girdle.

In the present case, the support conditions of the left arm influence the perpendicular forces the right hand applies to the hose in addition to the required mounting force. The complex conditions of equilibrium in these closed kinematic chains cause dependency between the forces in the system that are difficult to predict in the absence of a model that captures the system's inherent statical indeterminacy.

VALIDATION

The model and algorithms used in this example have been partially validated for other cases (see, for instance, Nolte et al. (2008) and Dubowsky et al. (2008)) but not for this particular application and it is therefore not certain that it predicts the correct forces. However, it is very likely that the prediction of dependency between support conditions and internal forces in the system is correct because it follows from the fundamental mechanics of the system, regardless of the precise muscle configuration and presumptions on muscle recruitment. Other muscle configurations and other recruitment criteria will predict different force values but independency between support conditions and internal forces can only occur if the system is statically determinate and this is definitely not the case.

The left gleno-humeral force of 621 N in the case of no left hand support is caused by the model retaining the left arm in the extended posture although the support is not used. In this case, it is not realistic that a real human would keep the arm in that position, so this figure is not representative for any real case.

CONCLUSIONS

In conclusion, musculoskeletal modeling with a plausible representation of the mechanics of the human body, including the ability to handle closed kinematic chains, can enable digital manikins to address a class of important ergonomic problems that cannot be plausibly simulated otherwise. On the other hand, the interactive features of typical digital manikin systems can make musculoskeletal modeling accessible to users in the ergonomics field. This requires a development effort with the purpose of putting musculoskeletal models "inside" digital manikins and providing the user interfaces with functions for detailed specification of boundary conditions and other properties specific to musculoskeletal modeling.

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