

# Introducing Stability of Forces to the Automatic Creation of Digital Human Postures

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## Abstract

Although the degree of automation is increasing in manufacturing industries, many assembly operations are performed manually. To avoid injuries and to reach sustainable production of high quality, comfortable environments for the operators are vital. Poor station layouts, poor product designs or badly chosen assembly sequences are common sources leading to unfavorable poses and motions. To keep costs low, preventive actions should be taken early in a project, raising the need for feasibility and ergonomics studies in virtual environments long before physical prototypes are available.

Today, in the automotive industries, such studies are conducted to some extent. The full potential, however, is far from reached due to limited software support in terms of capability for realistic pose prediction, motion generation and collision avoidance. As a consequence, ergonomics studies are time consuming and are mostly done for static poses, not for full assembly motions. Furthermore, these ergonomic studies, even though performed by a small group of highly specialized simulation engineers, show low reproducibility within the group.

Effective simulation of manual assembly operations considering ergonomic load and clearance demands requires detailed modeling of human body kinematics and motions as well as a fast and robust inverse kinematics solver. In this paper we introduce a stability measure rewarding poses insensitive to variations in contact points and contact forces. Normally this has been neglected and only the balance of moment and forces has been taken into account.

The manikin used in this work has 162 degrees of freedom and uses an exterior root. To describe operations and facilitate motion generation, the manikin is equipped with coordinate frames attached to end-effectors like hands and feet. The inverse kinematic problem is to find joint values such that the position and orientation of hands and feet matches certain target frames during an assembly motion. This inverse problem leads to an underdetermined system of equations since the number of joints exceeds the end-effectors' constraints. Due to this redundancy there exist a set of solutions, allowing us to pick a solution that maximizes a scalar valued comfort function.

Many objectives are included in the comfort function, for example in terms of joint angles, joint moments and solid objects' distance to the manikin. The proposed stability measure complements the earlier balance criterion and is combined into the comfort function. By increasing the importance of this function the digital human model will reposition to a more stable pose.

The digital human model will be tested on a set of challenging assembly operations taken from the automotive industry to show the effect of the stability measure.

*Keywords: Advanced biomechanical models, Ergonomics, Optimization Algorithm.*

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## 1. Introduction

Although the degree of automation is increasing in manufacturing industries, many assembly operations are performed manually. To avoid injuries and to reach sustainable production of high quality, comfortable environments for the operators are vital, see (Falck, Örtengren och Högberg 2010).

Poor station layouts, poor product designs or badly chosen assembly sequences are common sources leading to unfavorable poses and motions. To keep costs low, preventive actions should be taken early in a project, raising the need for feasibility and ergonomics studies in virtual environments long before physical prototypes are available.

Today, in the automotive industries, such studies are conducted to some extent. The full potential, however, is far from reached due to limited software support in terms of capability for realistic pose prediction, motion generation and collision avoidance. As a consequence, ergonomics studies are time consuming and are mostly done for static poses, not for full assembly motions. Furthermore, these ergonomic studies, even though performed by a small group of highly specialized simulation engineers, show low reproducibility within the group.

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This paper extends the work presented in (Delfs, o.a. 2012), (Bohlin, Delfs, o.a., Unified Solution of Manikin Physics and Positioning. Exterior Root by Introduction of Extra Parameters 2011) and is a part of the IMMA (Intelligently Moving Manikins) project (Hanson, o.a. 2011).

## 2. Manikin Model

In this section we present the manikin model and the inverse kinematic problem which includes positioning, balance, contact forces, collision avoidance, and comfort function (Bohlin, Delfs, o.a., Unified Solution of Manikin Physics and Positioning. Exterior Root by Introduction of Extra Parameters 2011).

### 2.1. KINEMATICS

The manikin model is a simple tree of rigid links connected by joints. Each link has a fixed reference frame and we describe its position relative to its parent link by a rigid transformation  $T(\vartheta)$ . Here  $\vartheta$  is the value of the joint between the link and its parent. For simplicity, each joint has one degree of freedom, so a wrist for example, is composed by a series of joints and links.

To position the manikin in space, i.e. with respect to some global coordinate system, we introduce an exterior root as the origin and a chain of six additional links denoted exterior links – as opposed to the interior links representing the manikin itself. The six exterior links have three prismatic joints and three revolute joints respectively. Together, the exterior links mimic a rigid transformation that completely specifies the position of the lower lumbar. In turn, the lower lumbar represents an interior root, i.e. it is the ancestor of all interior links.

Note that the choice of the lower lumbar is not critical. In principal, any link could be the interior root, and the point is that the same root can be used though a complete simulation. No re-rooting or change of tree hierarchy will be needed.

Now, for a given value for each of the joints, collected in a joint vector  $\theta = [\vartheta_1, \dots, \vartheta_n]^T$ , we can calculate all the relative transformations  $T_1, \dots, T_n$ , traverse the tree beginning at the root and propagate the transformations to get the global position of each link. We say that the manikin is placed in a pose, and the mapping from a joint vector into a pose is called forward kinematics. Furthermore, a continuous mapping  $\theta(t)$ , where  $t \in [0,1]$ , is called a motion.

### 2.2. Problem statement

In this paper we use a unified treatment of balance, contact forces, position constraints, ergonomics and collision avoidance etcetera. Often in practice, the number of constraints is far less than the number of joints of the manikin. Due to this redundancy there exist many solutions, allowing us to consider ergonomics aspects and maximizing comfort when choosing one solution.

Let  $x^T = [\theta^T, f^T]$  be the unknowns, i.e. the joint variables and the unknown forces and moments. Then we formulate the problem as follows:

$$\begin{cases} \text{maximize } h(x) \\ \text{while } g(x) = 0 \end{cases}$$

where  $g(x)$  are the kinematic constraints and  $h(x)$  is the comfort function. These are described in more detail below.

### 2.3. KINEMATICS CONSTRAINTS

In order to facilitate the generation of realistic poses that also fulfill some desired rules we add a number

of constraints on the joint vector. These kinematic constraints can be defined by a vector valued function  $g$  such that

$$g(x) = 0$$

must be satisfied at any pose. Finding a solution to this equation is generally referred to as inverse kinematics. In the following subsection we describe in more detail two specific parts of  $g$  dealing with balance and contact forces, and positioning constraints.

#### 2.4. BALANCE AND CONTACT FORCES

One important part of  $g$  ensures that the manikin is kept in balance. The weight of its links and objects being carried, as well as external forces and moments due to contact with the floor or other obstacles, must be considered. In general, external forces and moments due to contacts are unknown. For example, when standing with both feet on the floor it is not obvious how the contact forces are distributed between the feet.

#### 2.5. POSITIONING CONSTRAINT

Another common type of constraints restricts the position of certain links, either relative to other links or with respect to the global coordinate system. Typical examples of such constraints keep the feet on the floor, the hands at specific grasp positions and the eyes pointing towards a point between the hands. Positioning constraints are also expressed in the form  $g(x) = 0$ .

#### 2.6. COMFORT FUNCTION

When generating realistic manikin poses and motions, it is essential to quantify the ergonomic load. To do so, we introduce a scalar comfort function

$$h(x)$$

capturing as many ergonomic aspects as we desire. The purpose is to be able to compare different poses in order to find solutions that maximize the comfort.

The comfort function is a generic way to give preference to certain poses while avoiding others. Typically  $h$  considers joint limits, forces and moments on joints, magnitude of contact forces etcetera. Note that it is straightforward to propagate the external forces and moments and the accumulated link masses through the manikin in order to calculate the load on each joint. The joint loads are key ingredients when evaluating poses from an ergonomic perspective (Westgaard R och Aarås 1985).

It is convenient to let  $h$  also include collision avoidance, which is important for industrial simulations. It was shown in (Bohlin, Delfs, o.a., Automatic Creation of Virtual Manikin Motions

Maximizing Comfort in Manual Assembly Processes 2012) that a potential function which depends on distance makes the manikin able to avoid most collisions in a desirable way.

### 3. Stability

Because of the balance constraint, the manikin is in mechanical equilibrium in all poses. The balance constraint cannot distinguish between a stable and an unstable equilibrium, sometimes resulting in unnatural working poses. A pose in equilibrium is said to be stable if all forces and moments can be derived from a potential function  $V(q)$  and if  $\Delta V > 0$  for every nonzero virtual displacement  $\Delta q$ . On the other hand, if a  $\Delta q$  exists such that  $\Delta V < 0$ , then the pose is unstable (Howard och Kumar 1996).

The potential function for the manikin can be defined as the potential energy of a spring system if we represent the contact points as springs. Hence we introduce springs and stability in the next subsection, and in subsection 3.2 we describe in detail how stability is improved by an additive term  $h_s(x)$  of the comfort function.

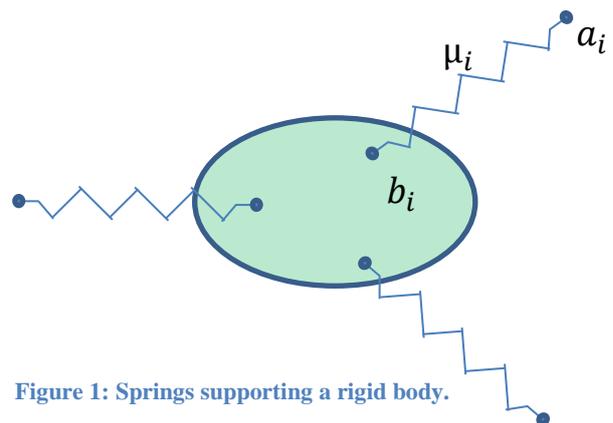


Figure 1: Springs supporting a rigid body.

#### 3.1. Springs and stability

Below a short explanation of springs and stability follows, for a more detailed study see (Selig 2001).

Consider a system of springs supporting a rigid body as in Figure 1. The springs have zero natural length and obey Hook's law with spring constants  $\mu_i$ . Let  $\tilde{a}_i^T = (a_i^T, 1)$  be fixed attachment points in space, and  $\tilde{b}_i^T = (b_i^T, 1)$  the corresponding attachment points on the rigid body when the body is in some standard 'home' configuration.

A spring system is at its most stable configuration when the potential energy is at its minimum. The potential energy is given by

$$\varphi = \frac{1}{2} \sum_i \mu_i (\tilde{a}_i - M\tilde{b}_i)^T (\tilde{a}_i - M\tilde{b}_i)$$

where  $M = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}$  is a rigid motion, written in the  $4 \times 4$  format, from the home configuration affecting the rigid body and its attachment points.

The stationary points can be found by considering paths of the form  $M(t) = e^{tS}M$  for an arbitrary screw  $S$ . Differentiating  $\varphi$  and setting  $t = 0$  yields

$$\partial_s \varphi = - \sum_i \mu_i (\tilde{a}_i - M\tilde{b}_i)^T S M \tilde{b}_i$$

which, for each screw  $S$ , must vanish at a stationary point. Eliminating  $S$  gives after some manipulation the two equations

$$\begin{aligned} \sum_i \mu_i a_i \times (a_i - Rb_i - t) &= 0 \\ \sum_i \mu_i (a_i - Rb_i - t) &= 0 \end{aligned}$$

The wrench for the screw  $S$  is  $W(S) = -\partial_s \varphi$ , and differentiating again gives the stiffness matrix

$$K = \partial_s W = \begin{pmatrix} \sum_i \mu_i A_i (RB_i R^T + T) & \sum_i \mu_i A_i \\ \sum_i \mu_i (RB_i R^T + T) & \sum_i \mu_i I_3 \end{pmatrix}$$

where  $A_i$  and  $B_i$  are the skewed matrix representations of  $a_i$  and  $b_i$  respectively. Furthermore, if origin is set to  $\sum_i \mu_i a_i$  we get

$$K = \begin{pmatrix} \sum_i \mu_i A_i R B_i R^T & 0 \\ 0 & \sum_i \mu_i I_3 \end{pmatrix}$$

Here, the lower right block  $\sum_i \mu_i I_3$  shows that the system has the same translational stiffness in any direction; this is a result of the zero length springs. Consequently, we restrict our attention to the upper left block which we from now denote by  $k$ , i.e.

$$k = \sum_i \mu_i A_i R B_i R^T$$

### 3.2. Manikin and stability

When attaching zero length springs at the manikin's contact points, the potential energy  $\varphi$  has clearly a minimum when  $a_i$  and  $b_i$  coincide for each  $i$ . If we let all spring constants be identical and choose the coordinate system such that  $a_i = b_i$ , the stiffness matrix simplifies to  $k = \mu \sum_i A_i^2$

Because the eigenvalues of the stiffness matrix  $k$  describe the rotational stiffness around corresponding eigenvectors (Van-Duc 1989), we can formulate a stability measure for the manikin in terms of the eigenvalues  $\lambda = [\lambda_1, \lambda_2, \lambda_3]^T$ .

The stiffness matrix has non-negative eigenvalues, but in order to be stable around any axis of rotation, all eigenvalues must be strictly positive. To give preference to stable postures, we choose the following function as a term in the comfort function to be maximized:

$$h_s(\theta) = \lambda_1 \lambda_2 \lambda_3$$

This function is smooth and easily differentiated,

$$\frac{\partial h_s}{\partial \lambda} = \begin{pmatrix} \lambda_2 \lambda_3 \\ \lambda_1 \lambda_3 \\ \lambda_1 \lambda_2 \end{pmatrix}$$

Clearly,  $h_s$  give precedence for even spread of the  $\lambda$  values.

The effect of  $h_s$  is that the contact points spreads out as long as no other constraints takes precedence, i.e. the feet spread apart for a more stable pose while still not stretching.

## 4. Results

To demonstrate the improvement made on the postures by introducing the stability objective into the comfort function, three cases are presented. In all cases the comfort function penalizes joint values near the limits and large moments in joints. Furthermore, close proximity to environment objects are penalized and in all the cases the same neutral state is the start of the calculation.

### 4.1. Lifting a box

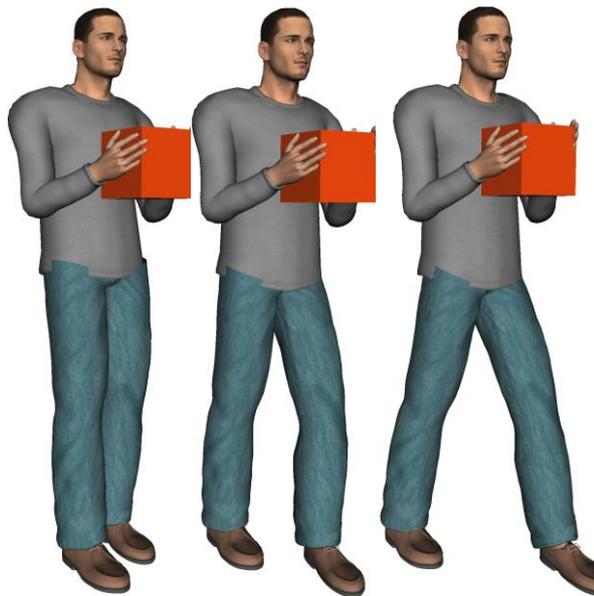
To make the effect of the stability objective easily distinguishable we let the manikin hold a 10kg heavy box with different values of the  $\alpha$  parameter. The manikin must grip it at the same position and orientation in all postures. The feet are allowed to slide on the floor and rotate around the surface normal of the floor – the remaining three degrees of freedom are locked. Three postures are calculated, with  $\alpha$  as 0, 0.1 and 1 as seen in Figure 2. The number of iterations and calculation time for each posture can be seen in Table 1.

Value of $\alpha$	0.0	0.1	1.0
Nr of iterations	43	40	45
Calculation time	0.02s	0.02s	0.01s

**Table 1: The table shows the effect the stability objective has on calculation time and number of iterations on the box lifting case.**

### 4.2. Tunnel bracket assembly

The second case is a part of a real assembly situation from the automotive industry and the goal is to generate a natural motion for the manikin assembling the tunnel bracket into the car. The path of the tunnel bracket was pre calculated by the software Industrial Path Solutions (IPS) (FCC 2013) and is guaranteed to be collision free. The manikin is then forced to follow the tunnel bracket through its path while fulfilling all other constraints. The hands should match the grasp positions on the tunnel bracket with five degrees of freedom locked – the palms are allowed to rotate around the surface normal. Furthermore, the feet are allowed to slide on the floor and rotate around the surface normal of the floor – the remaining three constraints.



**Figure 2:** The manikin is holding a box of 10kg. With  $\alpha$  as 0 in the left picture, 0.1 in the middle and 1 in the right picture.

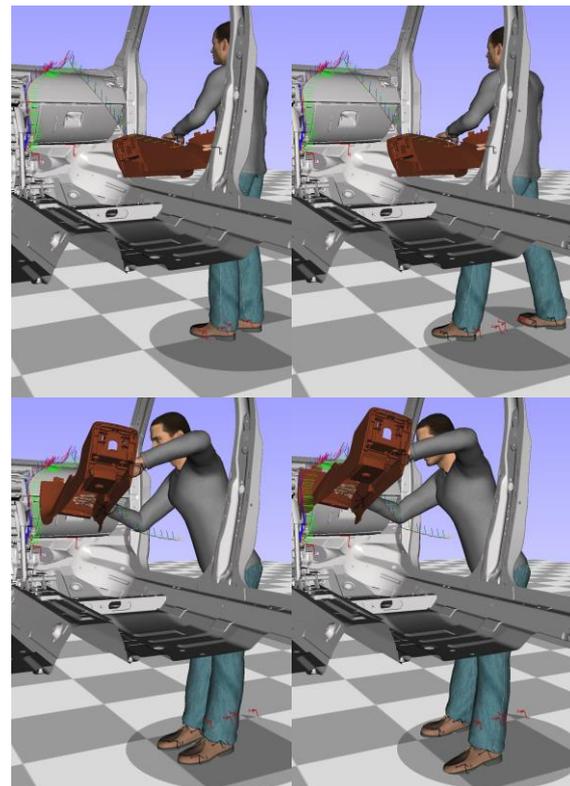
The hands should match the grasp positions on the tunnel bracket with five degrees of freedom locked – the palms are allowed to rotate around the surface normal. Furthermore, the feet are allowed to slide on the floor and rotate around the surface normal of the floor – the remaining three degrees of freedom are locked. Figure 3 show snapshots of the solution and Table 2 displays the number of iterations and calculation time for the two motions.

Value of $\alpha$	0.0	1.0
Nr of iterations	1756	1739
Calculation time	27.1	27.0

**Table 2:** The table shows the effect the stability objective has on calculation time and number of iterations on the tunnel bracket assembly.

#### 4.3. Seat mounting

In the third and last case, a seat is to be mounted into a car body. An auxiliary tool called a gripper is used to lift the seat while the manikin is guiding the seat. Both the path for the auxiliary tool and the seat is pre calculated by IPS and is guaranteed to be collision free. The right hand grips the auxiliary tool and the left hand grips the seat, both with all six degrees of freedom locked while the feet are allowed to slide on the floor and rotate around the surface normal of the floor – the remaining three degrees of freedom are locked. Figure 4 show snapshots of the solution and Table 3 displays the number of iterations and calculation time for the two motions.



**Figure 3:** A tunnel bracket assembly, with  $\alpha$  as 0 in the left figure and  $\alpha$  as 1 in the right figure.

Value of $\alpha$	0.0	1.0
Nr of iterations	1925	1965
Calculation time	27.1	28.0

**Table 3:** The table shows the effect the stability objective has on calculation time and number of iterations on the seat mounting case.

## 5. Discussion

In order to use a digital manikin for simulations and ergonomical evaluations, the postures and motions need to be as realistic as possible. The balance constraint makes the postures physically possible but they may still be unable to handle sudden force changes. The first case and its postures, see Figure 2, clearly shows how the posture get more stable as  $\alpha$  increases at the cost of larger joint angles and larger joint moments. Furthermore, as can be seen from the three cases, the stability objective adds the feeling that the manikin is handling force discontinuity even though the calculations are for static postures.

From the Tables 1, 2 and 3 it can be seen that the computation time for the postures and motions are not increased in any major way, if any. Hence the stability constraint can be used when there is force discontinuity, i.e. when lifting or pushing, without a large calculation overhead. An automated calculation of  $\alpha$  would make the motions more realistic and make the use of the manikin software for posture predictions easier.

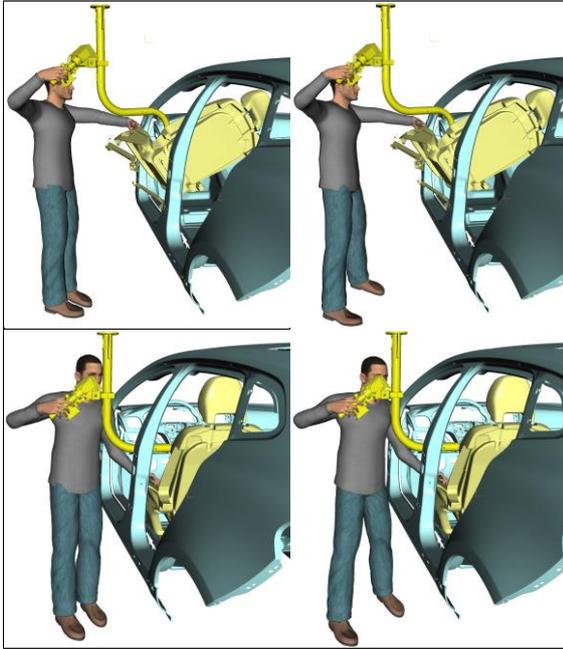


Figure 4: A seat mounting case, with  $\alpha$  as 0 in the left figures and  $\alpha$  as 1 in the right figures.

## 6. Conclusion

We add a stability objective to the comfort function which is based on the laws of stability in spring configurations. This gives more realistic postures and motions while it handles force discontinuity, without effecting the calculation time significantly. The stability function is successfully tested in combination with challenging assembly operations taken from the automotive industry.

We can therefore conclude that the stability constraint should be used when the manikin is to handle force discontinuity, i.e. when lifting objects, for more realistic postures.

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