Human Postures and Movements analysed through Constrained Optimization

by

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Abstract

Constrained optimization is used to derive human postures and movements. In the first study a static 3D model with 30 muscle groups is used to analyse postures. The activation levels of these muscles are minimized in order to represent the individual's choice of posture. Subject specific data in terms of anthropometry, strength and orthopedic aids serve as input. The aim is to study effects from orthopedic treatment and altered abilities of the subject. Initial validation shows qualitative agreement of posture strategies but further details about passive stiffness and anthropometry are needed, especially to predict pelvis orientation. In the second application, the athletic long jump, a problem formulation is developed to find optimal movements of a multibody system when subjected to contact. The model was based on rigid links, joint actuators and a wobbling mass. The contact to the ground was modelled as a spring-damper system with tuned properties. The movement in the degrees of freedom representing physical joints was described over contact time through two fifth-order polynomials, with a variable transition time, while the motion in the degrees of freedom of contact and wobbling mass was integrated forwards in time, as a consequence. Muscle activation variables were then optimized in order to maximize ballistic flight distance. The optimization determined contact time, end configuration, activation and interaction with the ground from an initial configuration. The results from optimization show a reasonable agreement with experimentally recorded jumps, but individual recordings and measurements are needed for more precise conclusions.

Descriptors: multibody system, optimal control, trajectory optimization, long jump, posture

Preface

This thesis studies the application of constrained optimization to derive human postures and movements. The first part gives a brief background, description of methods and conclusion about future work. The second part consists of the following papers:

Paper 1. Pettersson R., Bartonek Å. and Gutierrez-Farewik E.M., 2009
"Posture strategies generated by constrained optimization",
Submitted to Journal of Biomechanics

Paper 2. Pettersson R. and Eriksson A., 2009
"Movement optimization of multibody system subjected to contact constraint with application to long jump", Submitted to Journal of Biomechanics

Division of work between authors

The research project was initiated by Prof. Anders Eriksson (AE) who also was the main supervisor and advisor of the work resulting in Paper 2. Dr. Elena Gutierrez-Farewik (EGF) acted as co-supervisor and was advisor of the work resulting in Paper 1. Robert Pettersson (RP) continuously discussed the progress throughout the work with AE and EGF. Collaborate was Dr. Åsa Bartonek (ÅB).

Paper 1

The code development and simulations were done by RP with feedback from EGF. The experimental data were supplied from available measurements through ÅB. The paper was written by RP with input from EGF and ÅB.

Paper 2

The code development and simulations were done by RP with feedback from AE. The paper was written by RP with input from AE.

Contents

Part I

Introduction

CHAPTER 1

Introduction

1.1. Background

Simulation and modelling of biomechanical systems are used to give increased understanding about functioning from the cell to the musculoskeletal levels. Examples are chemical processes, material properties, blood flow, fractures, motion control, balance, and the areas treated here, human movements and postures.

Something that characterises modelling in biomechanics is the challenge to make a mechanical model, with its well defined degrees of freedom and properties, to represent a biological system where nonlinear materials, inconsistent centers of rotations, relatively soft tissue motions and subject control based on senses are present. Many times a trade off has to be done concerning which details that have to be represented to keep the most essential features. Modelling of multibody systems (MBS) like the human body are also done in robotics and computer graphics, which fields have developed efficient methods to evaluate the dynamics (Featherstone and Orin (2000)).

Optimization is an interesting research area in itself but is also frequently used in engineering sciences, for instance seeking a structural design based on minimal material usage, optimal control of processes and trajectory optimization within space exploration. In biomechanics applied to human musculoskeletal systems the optimization has become useful to solve ambiguous problems and/or to optimize some functional criteria. The load sharing problem in the redundant musculotendinous system (Amankwah et al. (2006); Heintz and Gutierrez-Farewik (2007)), the individual's choice of posture (Amankwah et al. (2006)) or targeted motions (Kaphle and Eriksson (2008)) are examples of ambiguous problems, while performance criteria such as maximum jump height (Andersson & Pandy (1998)) or length (Pettersson & Eriksson (2009)) are functional tasks. One can distinguish between dynamic and static optimization. Dynamic optimization takes time history into account while static versions only considers one time instant, possibly being one moment of a sequence. Dynamic optimization leads to large numerical costs which limits the number of degrees of freedom and inclusion of detailed muscle descriptions, but is required when deriving novel movements or having performance criteria dependent of time. For analysis of posture and gait, however, static optimization gives comparable results (Andersson and Pandy (1998)). With improved computational resources and optimization algorithms the size of the models possible to analyse has increased. Nevertheless, this is still a limiting factor for the simulations, especially in dynamic optimization.

1.2. Sports and medical application

The application groups of elite athletes and persons with motion disorders appear to be clear contrasts to each other. However, from a mechanical point of view, both groups generally strive for best possible performance, but within their individual limits.

The medical diagnoses among the subjects which have been initially studied are cerebral palsy (CP), Myelomenigocele (MMC) and Arthrogryposis Multiplex Congenita (AMC). Biomechanical limitations brought by Cerebral palsy can be different levels of muscle weaknesses, limited ranges of motion (ROM) and spasticity (stretch velocity induced tonus)(Gage 2004). Spasticity is therefore impossible to model in a static model unless simplifying it into a limit of ROM or as muscular forces constrained to fixed values. However, studies of the effect of reduced spasticity through treatment can be done. Since also perception and cognition disorders are often present, this group can be difficult to model with mechanical concepts. Despite the limitations it is still a justified application group because of the varying levels of disability in this large patient group.

MMC is caused by an innate hernia of the spinal cord. The most prominent symptoms of MMC are paresis and reduced sensibility in lower extremities. Dependent on the level of the hernia different muscles are affected. Contractures and skeletal deformities can be present from birth, but also developed during growth because of increasing strength in non-affected muscles (Becklund 2002).

The symptoms of AMC are innate contractures caused by hypoplasi or aplasi (incompletely development or absence) of muscle groups (Ortopedi 2004). Accordingly limited ranges of motion and weaknesses are the biomechanical limitations.

In sports applications there are many abilities which characterise athletes, such as agility, speed, power, flexibility, strength and coordination. These properties are not independent of each other and some of the properties are of more importance than the others, dependent on the application. In the athletic long jump all are important but what is more is that a balance must exist between speed, strength and technical requirements (Graham-Smith and Lees 2005). Flexibility is also essential but only such that the ROM not limit the movements. This group is highly evolvable through technique and specific physical training, which makes it an interesting application to be able to study possible improvements to their performance.

1.2.1. *Standing posture*

A basic condition for quiet standing is to keep the center of mass (COM) of the whole body within the base of support (BoS) formed by the feet. Then the posture is the chosen configuration to fulfil this condition and describes the orientation of the body segments relative to the gravitational vector, i.e., it is an angular measure from the vertical (Winter 1995).

At quiet standing the ground reaction force (GRF) and the gravity force act towards each other and the slightest misalignment will contribute to a moment driving to increase this misalignment, thus the mechanical system is unstable and demands active control to keep the balance. The human continuously tries to control the musculoskeletal system by activating muscle groups in a coordinated way but cannot control the system without a resulting sway.

To maintain balance, there are two strategies to compensate for a movement of the COM. These are either moving the center of pressure (COP) with respect to the vertical projection of the COM or by counter-rotating segments around the COM (Hof 2007). The first strategy can be used when the COM is within the BoS and has limited velocity. Counter-rotating segments can always be used but is most useful when it is not possible to move the COP any further. In Hof (2007) the results suggest that the counter-rotating strategy is more important with a narrow BoS.

In this work the subject group is able to balance into almost quiet standing so a static model has been assumed to be sufficient to represent the standing posture. However, there are still many factors that can have effect on the choice of posture. Subject properties in terms of anthropometry and flexibility (Rybski 2004), muscle strength (Kuo and Zajac 1993) and obesity (Gilleard and Smith 2007) together with orthopedic treatments like orthoses (Owen 2004) and heel lifts (Owen 2004; Eslami et al. 2006; Rodriguez and Aruin 2002) influence the posture.

The problem of choosing a posture strategy can thereby be described as a three dimensional link structure controlled by a redundant control system where load sharing and configuration are sought which minimize the required activation levels.

1.2.2. *Long jump*

The athletic long jump and particularly the take off is an action which is totally dependent on high levels of coordination and intensity. The ground contact time is approximately 110 ms (Luthanen and Komi (1979)) during which the jumper gains the vertical momentum needed for the jump. In simple terms the jumper should gain as much vertical momentum as possible while trying to keep the horizontal speed already gained in the run up. This can however be realized in different ways and important factors have been studied in literature. High correlation between horizontal speed and jumping length has been shown (Hay (1993)), optimal take-off angles have been analysed by Linthorne et al. (2005), and the importance of angle of attack and muscle architecture have been studied by Seyfarth et al. (2000). The quick action also emphasises the importance of muscle dynamics. The spring-like effects which can be enhanced by pre-activation and high velocities and forces in the eccentric phase (Kyrolainen et al.

(2003)) are investigated by Seyfarth et al. (2000) who conclude that the jumping distance is sensitive to this feature. This is a property which justifies the often emphasized importance of footplant velocity. In GRF measurements of a take-off (Seyfarth et al. (2000); Hatze (1981); Muraki et al. (2008)), one can observe two separated peaks, where the first is introduced by the initial impact and passive properties and the second by active push-off. These measurements also show the importance of the initial impact, which contributes to approximately 25% of the total change in momentum (Seyfarth et al. (1999)).

The mechanical representation of the long jump take off can be summarized as a multibody system subjected to a contact constraint, and for which the coordination is sought to maximize the following flight distance.

1.3. Aim and scope

1.3.1. *Posture strategies*

The main objective was to develop a tool for investigation and prediction of how different aids, such as orthoses and heel lifts, affect standing posture in order to justify and thereby to explain clinical experiences about posture and treatment planning.

One milestone was to develop a simulation tool simple enough to be used in a clinical setting. Therefore a 2D-model was created. The simulations should be subject specific and allow the user to specify the properties found during a clinical assessment. Due to the characteristics of the subjects, a 3D model, where asymmetry and more detailed properties of the muscle system can be defined, was needed for more accurate and reliable simulations.

1.3.2. *Movement optimization*

The objective was to formulate a solution methodology for the study of movement optimization of a multibody system subjected to contact constraint. Here with an application to long jump. Some main problems to solve were to include sufficient numbers of mechanical degrees of freedom for an accurate representation of the human body, still keeping the number of variables low in the optimization. The interaction of the mechanical model with contact constraints should also be considered in the optimization. Another feature, which has great effect on the characteristics of the problem, is that the simulation should not be based on measured motion, but to create novel movements.

1.4. Outline of thesis

The methods used in the papers are described in Chapter 2. Along with used methods some orientation is given about alternative methods used in literature and for future work. Chapter 2 also includes a short description of the applications of the methods. In Chapter 3, reviews of the two papers are found. In Chapter 4, the main conclusions from the papers and some ideas for future work are discussed. The second part of the thesis consists of the resulting papers.

CHAPTER 2

Methods

2.1. Mechanical representation of the body

2.1.1. *Link structure*

The body segments have been modelled with rigid links in the following applications. This is a well motivated assumption since the skeletal structures are stiff and the compression is small compared to the relative movements of the body segments. However, when studying the effect of an impulse acting on the body this matter should be considered, since tissue deformation decreases the resulting stress in the system. The joints are represented with hinge or ball and socket joints with well defined degrees of freedom (dof). In reality the motion is more complex. At the knee joint, mainly acting like a hinge joint, the motion follows a path containing both flexion/extension, rotation and translation (Hamill & Knutzen 2009). A consequence of using rigid links is also that the inertia properties are constant, which makes modelling less complex.

The above described mechanical model is undamped although in many dynamic applications, including long jump, the inclusion of damping and distributed mass is required (Seyfarth et al. 2000). To represent this, a wobbling mass has been attached to the rigid link structure with spring and damper elements. A drawback is the extra dof which are needed to represent the complete motion.

2.1.2. *Muscle system*

The muscles are the driving component in the musculoskeletal system. The muscle system is complex and needs to be simplified in a numerical model. These simplifications can be done to different extents. Joint actuators can be used to represent the muscle groups acting at each joint (Ashby and Delp 2006; King et al. 2006; Andersson & Pandy 1998). When using joint actuators one can introduce varying maximum strengths along the ROM to represent the effect of muscle length and moment arm (Pettersson & Eriksson 2009), thereby improving the muscle system model. There are also various models in literature where passive stiffness, representing the passive resistance within and at the end of ROM, is included as an additional moment to the muscles (Amankwah et al. 2006). A further step towards a more detailed description of the muscle system is to introduce muscles and muscle groups (Delp et al. 1990;

Spägele et al. 1999; Andersson and Pandy 1998). With this formulation biarticular muscles can be included and similarly also muscle lengths and moment arms. In this thesis, muscle data have been collected from SIMM (Delp et al. 1990). With separate muscle groups, including biarticular muscles, the system becomes redundant such that a specific load can be carried by many different feasible solutions of force distribution in the system. This problem has been dealt with in literature (Amankwah et al. 2006; Andersson & Pandy 1998; Rasmussen *et al.* 2001; Heintz and Gutierrez-Farewik 2007) and optimization has become a standard method, but together with different optimization criteria. Muscle effort, measured by muscle stress or activation level, is often used. A common simplification of the human body is to make a 2D model when the major movements take place in one plane. As a consequence, the already redundant muscle system becomes even more so, as muscles with different functions in 3D are modelled as parallel in 2D.

In a dynamic situation the muscle has variable capacity dependent on contraction velocity, activation history and muscle dynamics. In the type of simulations performed here the possibilities to include advanced muscle dynamic description are limited due to computational demands. However, factors compensating for contraction velocity can be included without complications (Ashby and Delp 2006). The total moment about a joint was here chosen to be

$$M = \alpha \, \theta \left(q \right) \phi \left(\dot{q} \right) f_{\max} \tag{2.1}$$

where α is the activation, $f_{\max}$ the maximum isometric force, θ a factor for moment arm and muscle length, and ϕ a factor compensating for concentric or eccentric movements.

One component in the muscle dynamics which is mentioned by Luthanen and Komi (1979); Seyfarth et al. (2000) to be important in the long jump take-off, is the spring-like effect in a muscle when working interactively with its tendon, which is the stretch-shortening cycle (SSC), (Komi 2000; Stålbom 2008). However this feature is not modelled in this work.

2.1.3. *Predefined intersegment relation*

A segment's motion can be strongly dependent on the orientation of prior and following segments in the kinematic chain due to biarticular muscles, flexibility and stretching stiffness along the ROM. In Anderson et al. (1986) a second order polynomial of knee and torso angle is derived, based on trunk tilt motion for four different knee angles.

$$S = -17.519 - 0.11863T + 0.22687K + 0.0011904TK + 0.00499T^2 - 0.000753K^2 \tag{2.2}$$

Where T is the trunk's angle relative the vertical and K is the knee angle, the relative angle between thigh and shank. The results in their work also suggest that the same model can be applicable to unexperienced subjects. For subjects with disabilities, this relation should be modified. Here a least square fit of motion captured data was used to derive the coefficients. The procedure is simple but can lead to problems when used at a clinic since it requires relatively controlled motions from subjects, who often suffer from motor or communication disorders. In the absence of biarticular muscles and without consideration of stretching stiffness along the ROM in the simplified 2D model, this relation is an alternative, even though the use of predefined intersegment motions introduce a limited ability to perform parameter studies of hip motions.

2.2. Optimization

The general constrained optimization problem can be stated as

$$\begin{aligned} &\min_x f(x) \text{ subject to} \\ \\ &c(x) \leq 0 \\ &ceq(x) = 0 \\ &lb \leq x \leq ub \end{aligned} \tag{2.3}$$

where x is a vector containing all the variables, f is the scalar function to be minimized, c and ceq are inequality and equality constraints, respectively. The borders lb and ub are the lower and upper bounds of the variables in x. To solve this problem the function `fmincon` in Matlab (MathWorks Inc., Natick, USA) optimization toolbox, was used. The function is based on sequential quadratic programming and requires continuous object function and constraints.

2.2.1. *The static optimization problem*

The static optimization formulation is relatively straightforward and similar formulation can be found in literature (Amankwah et al. 2006; Heintz and Gutierrez-Farewik 2007) to solve the load sharing problem. However, the present optimization also solves for the configuration of the multibody system. So the activation level for each muscle group together with a coordinate and a moment in each dof are the variables in the optimization. The cost function which represents the individual's choice of posture is here representing the needed effort for a specific posture. The basic cost function is $f = \sum \alpha_i^2$, but in one application an additional term is added: a penalty for resting at the end of ROM simulating discomfort, $f = \sum \alpha_i^2 + \frac{\text{passive moment}}{\text{nominal moment value}}$.

In the inequality constraints we find the requirement for static stability that the projection of COM should be within the BoS, the parallelogram formed by the feet. The inequality constraint also ensures that the friction forces are less than available with the specific friction coefficient used (here $\mu = 0.5$).

The equality constraints consist of the equilibrium equations, the orthosis functions and the predefined intersegment motion, if applied.

2.2.2. *The dynamic optimization problem*

Several methods exist for solving trajectory optimization problems in literature, e.g. indirect and direct shooting methods, and global and local collocation methods (Betts 1998). Dependent of the availability of a nonlinear optimization solver the problem should be formulated to fit the general form of optimization (Eq. 2.3). One common strategy in movement optimization in biomechanics is to introduce time discretization (Eriksson 2007; Fang & Pollard 2003; Pandy *et al.* 1992) in order to have discrete variables representing the motion over time.

In the present work, Paper 2, a combination of shooting method and local collocation was used. The degrees of freedom which represent physical joints in the application, and which are controlled by the subject were represented by fifth-order time polynomials separated by N_n nodes. In order to have variables representing physical measurements, i.e., position, velocity and acceleration, shape functions were used between the nodes. Hence the trajectory in each degree of freedom can be evaluated between the time nodes as in Eq. (2.4). It was also experienced that the use of the naive form of polynomial $P = a + bt + ct^2 + dt^3 + et^4 + ft^5$ gave poor behaviour in the optimization, due to lacking orthogonality of the polynomial terms. The coefficients, in the optimization, got values in different orders of magnitude and solutions which were close in the physical solutions but separated in the numerical ones. The interpolation of each coordinate was thereby seen as:

$$q_i(t) = N_1^i(t)q_i^{t=t_i} + N_2^i(t)\dot{q}_i^{t=t_i} + N_3^i(t)\ddot{q}_i^{t=t_i} + N_4^i(t)q_i^{t=t_j} + N_5^i(t)\dot{q}_i^{t=t_j} + N_6^i(t)\ddot{q}_i^{t=t_j} \ , \ (t_i \le t \le t_j) \quad (2.4)$$

The time domain was broken into n_{t} smaller time steps, the size of the integration steps. The control (activation α) at each time step and the position, velocity and acceleration at each node in each dof chosen as design variables in $\boldsymbol{x}$, according to

$$\boldsymbol{x} = [\boldsymbol{Q} \ , \ \boldsymbol{A}] \quad (2.5)$$

where

$$\boldsymbol{A} = [\alpha_{1st\,dof}^{t_0} \ , \ \alpha_{2nd\,dof}^{t_0} \ , \ \dots \ , \ \alpha_{Last\,dof}^{t_0} \ , \ \alpha_{1st\,dof}^{t_1} \ , \ \dots \ , \ \alpha_{Last\,dof}^{t_{n_t+1}}] \quad (2.6)$$

$$\boldsymbol{Q} = [q_{1st\,dof}^{0} \ , \ \dot{q}_{1st\,dof}^{0} \ , \ \ddot{q}_{1st\,dof}^{0} \ , \ q_{1st\,dof}^{1} \ , \ \dot{q}_{1st\,dof}^{1} \ , \ \ddot{q}_{1st\,dof}^{1} \ , \ \dots \ , \ q_{1st\,dof}^{N_d} \ , \ \dot{q}_{1st\,dof}^{N_d} \ , \ \ddot{q}_{1st\,dof}^{N_d} \ , \ q_{2nd\,dof}^{0} \ , \ \dots \ , \ \ddot{q}_{Last\,dof}^{N_d}] \quad (2.7)$$

In the dof which represented non-physically controlled dof (dof of contact and wobbling mass) forward integration was used. The use of forward integration instead of having design variables representing the contact and wobbling mass avoided to me convergence problems in the used solver (fmincon). With this formulation, the gradients of constraints and object function are not available, reducing the convergence speed.

In the following application to long jump, two fifth-order polynomials were used in each degree of freedom to keep the number of variables in the optimization as low as possible. This was possible, as the expected motion did not contain any oscillations. A variable transition time was used to let the structure have an ability to rapidly adjust for the ground contact. The number of time steps used were $n_\mathrm{t} = 44$, so the total number of design variables in the optimization became $270 = (9 + (n_\mathrm{t} + 1)) \times 5$

The object function was the horizontal length of the flight trajectory which only is dependent on the positions and velocities in the last time node. Since the contact and wobbling mass are forward integrated, the dynamics function has to be integrated over the whole simulation time in order to evaluate the object function.

The equality constraints ensures that the required generalized forces are equal to the generated moments of the muscles (activation times the factors considering moment arm, contraction velocity and maximum isometric strength at the specific joint) for any feasible solution of the optimization problem.

$$c_{eq} = \tau_i^j - \alpha_i^j \theta \left(q_i^j \right) \phi \left(\dot{q}_i^j \right) f_{i,\, max}$$
$$(\, i = \{\text{number of dof}\}\, ;\, j = \{\text{number of time step}\}) \tag{2.8}$$

2.3. Equations of motion

There exist several alternative procedures to derive the equations of motion for an MBS. Dependent on the size and topology of the systems representing the human body two approaches have been used. The natural approach to derive the equations of motion for a system of moderate size is to use the Euler-Lagrange equations. These are derived from energy expressions using any symbolic mathematical and analytical software (here Maple(Maplesoft, Waterloo Maple Inc, Canada)), resulting in N_d equations and N_d unknowns.

$$L = T - V \tag{2.9}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = Q_i \;\; for \;\; i = 1..N_d \tag{2.10}$$

Where T is the kinetic energy, V the potential energy and Q the nonconservative generalized forces. This is a convenient approach but the computational cost increases drastically with increasing size of the MBS in terms of dof and number of links. The derivation and size of the analytical expressions becomes unmanageable with the software and computer resource used. Furthermore, the computational cost to solve the $N_d \times N_d$ system of equations increases by $O(N_d^3)$. This method was used in the application to posture strategies, where the expressions became manageable by describing the system from its most center positioned segment (pelvis in this application) in order to have as short kinematic chains as possible. The system was also reduced by cancelling the terms including $\dot{q}_i$ and $\ddot{q}_i$ to make the equations static.

In order to enable modelling of future increasing sizes of systems an alternative method was used. In computer graphics and robotics the need for efficient algorithms to model realtime situations is present. There are several methods developed for this purpose, but the Articulated Body Algorithm (ABA) (Featherstone 1987) is one of the fastest linear complexity algorithms for linked bodies without closed loops (Kokkevis & Metaxas 1998).

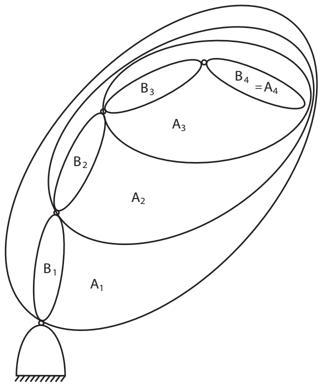


Figure 2.1: Kinematic chain with defined articulated bodies. Re-drawn from Featherstone (2008).

The main idea is to determine properties of groups of bodies, articulated bodies (Fig. 2.1), allowing them to be treated as single rigid bodies but with articulated-body properties. The equation of motion for a body in a linked structure can be written as

$$\boldsymbol{f}_i = \boldsymbol{I}_i^A \, \boldsymbol{a}_i + \boldsymbol{p}_i^A \tag{2.11}$$

using spatial notation (6 dof vectors). Here, $\boldsymbol{f}_i$ is the force in joint i, $\boldsymbol{I}_i^A$ is the articulated-body inertia, $\boldsymbol{a}_i$ the spatial acceleration of body i and $\boldsymbol{p}_i^A$ the bias force for body B_i in the articulated-body A_i. The articulated-body inertia depends on the rigid-body inertia of the members, and of their instantaneous kinematics, and the bias force depends on velocity effects and forces acting on the articulated-body. Now, using that the equations of motion of two linked bodies are rather simple (Eq. 2.11), the problem is turned into evaluation of the properties of the Articulated-bodies (Fig. 2.1). Recurrence relations, where $\boldsymbol{I}_i^A$ and $\boldsymbol{p}_i^A$ can be expressed in terms of $\boldsymbol{I}_{i+1}^A$ and $\boldsymbol{p}_{i+1}^A$, allow the equations of motions be evaluated linearly in time.

The accelerations are then derived in three loops: one outwards to calculate velocities and forces arising from velocities, one inwards loop for the articulated-body inertias and bias forces, and a second one outwards to calculate the accelerations.

The original ABA is a forward dynamics algorithm for a kinematic chain with fixed base. However with the modifications presented in Featherstone (2008) a floating base (free to move in plane) was introduced, and the ability to solve hybrid dynamics problem (forward and inverse kinematics at different joints, i.e., rheonomic constraints). The final function call uses the position and velocity in all dof, the acceleration in the inverse dof and the forces in the forward dof as input.

$$[\boldsymbol{\tau}_{inv}, \ddot{\boldsymbol{q}}_{fwd}] = DynamicsFunction(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}_{inv}, \boldsymbol{\tau}_{fwd}) \tag{2.12}$$

2.4. Contact

There are mainly two ways to model the contact: rigid body contact(kinematic constraint) and compliant contact. In the method developed by Hatze (1981) and applied to long jump, a formulation is used which changes the velocity instantaneously by applying an impulse such that the contact constraint is fulfilled. The contact force $\boldsymbol{\tau}$ will go to infinity when time approaches zero but the required impulse will be finite.

$$I = \lim_{\delta t \to 0} \int_{t}^{t+\delta t} \boldsymbol{\tau} dt = \boldsymbol{h}(t + \delta t) - \boldsymbol{h}(t) \tag{2.13}$$

To stabilize a kinematic constraint and damp out the following round-off errors, a Baumgarte stabilization method is used (Baumgarte 1972). An efficient formulation of constraints of this type has been developed to be used together with ABA (Kokkevis & Metaxas 1998) which should be considered if more complex contact simulations are modelled together with MBS.

However, here a compliant contact (Eq. 2.14) has been used since it can represent the physical problem with the foot deformation at contact.

$$\tau = k\,q + c\,\dot{q}\,q \tag{2.14}$$

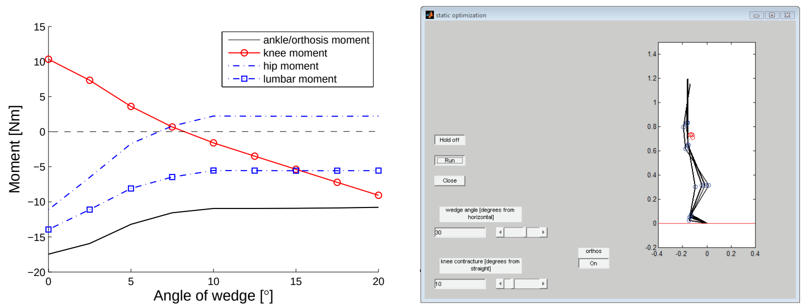
The multiplication by q in the damping term is used to make the constraint continuous which was a requirement in the optimization. Advantages are that initiating contact and contact loss can be solely determined from position and velocity; no linear complementary problem has to be solved as when using kinematic constraints. The main drawback is that this formulation introduces a tendency to high frequency vibrations in the system, requiring smaller steps in the integration or increasing numbers of time stations when discretizing the trajectories. Soft contact has been used by Wilson et al. (2006); Ashby and Delp (2006). None of these mention the problem with optimization encountered in this work. With the formulation where the contact was integrated forward, and the dof representing the contact were not included as optimization variables, the convergence problems were avoided.

2.5. Applications

2.5.1. *Tool for modelling of sagittal (2D) standing posture*

Initially, a 2D-model for standing was created and the postures were based on minimization of joint moments. This project was presented at the Annual Meeting of ESMAC 2007 (Pettersson *et al.* 2007). The static optimization formulation and the predefined intersegment relation was used. The user specifies the subject properties in a text file in terms of ROM, anthropometry and weaknesses. Then the user can run simulations where orthosis, heel lift and contractures can be modified (Fig. 2.2). The results can be observed as stick figures but also as numbers for resulting joint angles and moments. Since the mechanical problem is small the optimization converges easily as long as there exists a feasible solution for the problem stated.

The intention with this work was to create a tool which allow users without engineering knowledge to run subject specific simulations.



(a) (b)

Figure 2.2: The 2D-simulation tool a) a parameter study of heel lift in the 2D model: moment at the joints b) Screen shot of the 2D-simulation tool.

2.5.2. *3D model for standing posture*

In order to allow studies of a subject with asymmetries, a 8 segment 3D model was created (Fig. 2.3). The static optimization formulation was used, but not the predefined intersegment relation for pelvis orientation. Instead, a muscle system including 30 muscles or muscle groups (Table 1) was used. With its varying moments arms and maximum strengths along the ROM, a weaker intersegment relation was introduced. The simulations with this model required more manual control due to the increased complexity in the MBS and the load sharing problem. Here, the user can study posture strategy, joint moments, muscle activation level and orthosis effect.

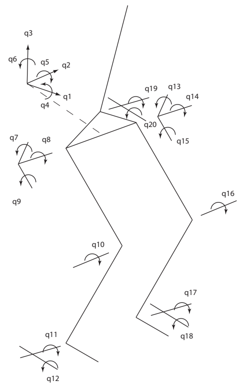


Figure 2.3: The mechanical model

Function	Muscles	No.
dorsiflexion	tib_ant, per_t, ext_d, ext_h	1
plantarflexion	med_gas, lat_g	2
	soleus, tib_p, flex_, flex_, per_b, per_l	3
	semimem, semit	4
knee flexion	med_gas, lat_g	2
	semimem, semit	4
	bifemsh	14
knee extension	rect_fem	6
	vas_med, vas_i, vas_l, pat_l	7
hip flexion	rect_fem	6
	add_long, add_b, pect, grac	8
	glut_med1, glut_min1, sar, tfl	9
hip extension	semimem, semit, bifem	4
	glut_max2, glut_max3	5
	add_mag1, add_mag2, add_mag3	10
	glut_med3, glut_max1, glut_min3	11
hip abduction	glut_med1, glut_min1, sar, tfl	9
	glut_med3, glut_max1, glut_min3	11
	glut_med2, glut_min2, peri	12
hip adduction	semimem, semit, bifem	4
	add_long, add_b, pect, grac	8
	add_mag1, add_mag2, add_mag3	10
hip internal rotation	glut_med1, glut_min1, sar, tfl	9
hip external rotation	quad_fem, gem	13

Table 2.1: Muscle groups and their function.

2.5.3. *Long jump*

A six link model with a wobbling mass was used to represent the human body in the long jump take-off (Fig. 2.4). The foot contact was modelled with spring and damper elements. The ABA was used to evaluate the dynamic functions. The dynamic optimization formulation was used, where the model finds optimal movement in terms of a following jump distance from an initial configuration. Activation history, ground contact time and movement are all determined by the optimization.

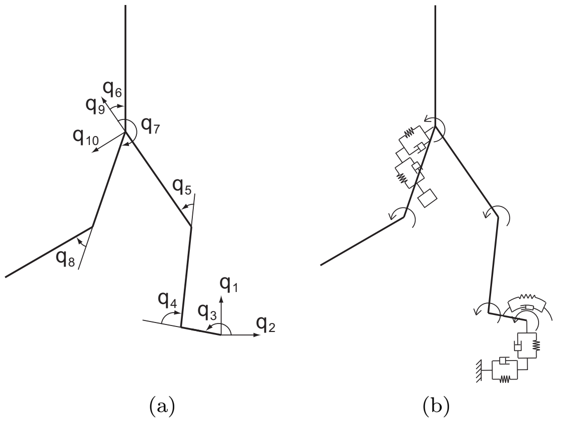


Figure 2.4: The mechanical model: a) degrees of freedom, b) properties for the forward integration.

CHAPTER 3

Review of papers

3.1. Paper 1

The aim was to develop a calculation tool for the study of the posture strategies among persons with motion disorders. Furthermore the simulations should be subject specific such that individual variations in anthropometry, strength and orthopedic aid are considered. A three dimensional static model with 8 segments was used. The muscle system was represented by 30 muscles or muscle groups, corresponding to their different functions in terms of working direction and biarticular muscle effects at multiple joints. Contractures can be defined and orthoses were included as torsional springs, if present. The muscle strengths were based on available normative data but were modified for weaknesses found during clinical assessment. The chosen posture strategies were then based on the configuration minimizing the sum of activation levels of the muscle groups, referred to as the required effort.

The simulations were initially compared to experimental results. There was qualitative agreement in the overall posture and position of COM but specific segment orientations disagreed at times. The orientation of the pelvis segment in sagittal plane was the variable with the highest deviation. Suggestions of improvement are proposed such as including passive stiffness along ROM. Additional measurements to derive a predefined intersegment relation can be relevant. Asymmetries in strength or in anthropometry can be modelled, thereby also allowing investigation of changes in subject properties. This is examplified by a parameter study where the orthosis angle was varied and the resulting efforts, joint moments and specific muscle activation levels were compared.

3.2. Paper 2

The aim was to formulate a solution methodology for movement optimization of multibody systems subjected to contact constraint. In this work the application of the long jump take off was studied. A sagittal model with six rigid links and one wobbling mass was used. The contact was modelled with a soft contact, with its pros and cons. The movement in each degree of freedom representing the physical joints was described by two fifth-order polynomials, while the motion in the degrees of freedom of the contact and wobbling mass was integrated forwards, as a consequence. Using a functional performance criterion in an optimization, novel movements were derived from an initial configuration. This means that the result is a coordination of the movement, from an initial position and velocity at foot plant until foot off. The solution maximizes the ballistic flight distance following take-off. The optimization determines contact time, end configuration, muscle activation and interaction with the ground.

In the simulations, the initial configuration and velocities, together with the properties of the muscle system and the anthropometry, were based on available data in literature. The results from the optimization were then compared with published experimental recordings of the long jump. There was reasonable agreement in terms of ground reaction force, joint moments and movements. A sensitivity study was also performed for some basic parameters, such as polynomial division, contact time and muscle activation rate.

CHAPTER 4

Conclusions from papers and future work

When dealing with biomechanics, one natural and always present example of future work is to improve the physiological representation. A topic in which there is incomplete knowledge is the neurological control system. In this project a central part of the work has been to represent this complex control by constrained optimization. Standing postures and human movements are then modelled with the explained assumptions (Chapter 2).

4.1. Standing Posture

The use of optimization to model standing posture strategies seems promising. With such a formulation many parameters, such as weaknesses, contractures and orthoses, can be considered which would be difficult without a systematic procedure. The results can also be analysed on different levels ranging from specific muscle activations, to joint moments and to overall effort.

The use of muscle activation and coordinates as design variables allows the optimization to solve the load sharing problem, but also to represent the choice of posture, which has been proved to be numerically infeasible in an application of dynamic optimization (Andersson & Pandy 1998). Orthopedic aids like orthoses can be modelled. This is a valuable possibility, since creation of the aids can be based on more information, and on an understanding of the effects of the properties of the aids.

Further validation to larger groups of patients will be performed to study the capabilities and shortcomings of the model. At present, there are ongoing projects at MotorikLab (Astrid Lindgrens Children's Hospital, Stockholm) which will make a more extensive validation possible.

To improve the input data in terms of ranges of motion, the values should be based on the actual ranges of motion the subject can have while standing. This refers to, for instance, the shank orientation for a subject with constrained dorsiflexion using conventional assessment, which can have extensive forward lean when standing due to eversion at ankle and bending at the knee.

There are some limitations that should be considered in the future work. One of the limitations is that the lengths of biarticular muscles are not considered. Including this feature means that flexion at one joint can affect ROM at another. Together with refinement of anthropometry, especially for the lower back, such an aspect would most probably improve the predictions of pelvis orientation.

The model is also limited, in the sense that it can only simulate subjects able to sustain quiet standing. Since the model is static, balance can only be accounted for by decreasing the size of the base of support. Spasticity which is a dynamic phenomenon needs to be simplified to its actual outcome, a limited ROM. However, this application should be used with caution even if this will exclude many patients from study. Pain, which is a subjective measure, cannot be modelled but a penalty into the optimization for putting stress at some joint can be used to simulate discomfort.

4.2. Optimal movements

A formulation for optimization of movements of a multi-body system subjected to contact constraints has been developed. The resulting simulations derive the movements from an initial state, in order to maximize a functional criterion, here the flight distance following take-off in athletic long jump.

With the successful solution procedure many new questions arise about the parameters of wobbling mass and ground contact properties. However, there are some practical characteristics which limit the possibilities to run extensive parameter studies at present. When starting from a new initial condition, or with some new contact properties, the calculations take about four days of computer time. Sometimes an already converged solution can be used as starting guess in the optimization which reduces the computational time. An alternative procedure to tune the model would be to have detailed measurements of a long jump take-off, with ground reaction force, full body motion capture and subject properties, where simulations can be performed with known motion but solving for the sought parameters. This would simplify the calculations since it is the optimization of novel movements which is numerically costly. Based on the recorded and synthesized movements, smaller or larger variations to the techniques can then be simulated with reasonable resources.

The results from the simulations are so far only described with resulting jump length and trajectories of muscle activation, coordinates and their velocities. In future it would be useful to determine a number of measurements which could be directly interpreted in practical terms. For instance, how much the swing leg or the arms contribute to the final jump length, and to give suggestions of how their coordination could be improved or which the limiting factors are for such improvement.

The present model finds optimal movement from fixed initial configuration and velocities. An alternative could be to seek the optimal preparation for the take-off by relaxing the constraints on initial condition into constraints on the center of mass position and velocity, both expressed with some intervals.

4.3. Other applications of the same method

The use of simulations in combination with motion capture could serve as a diagnostic tool. Once motions are collected, the simulations can give measurements and numbers for what is characteristic for a specific motion. This could be applied to both posture strategies and movement patterns.

Different events in sports are natural examples of future applications. The simulations can give further information about technique and limiting factors of performance for a specific event on individual basis. This requires development of a new mechanical model adapted for each event to receive valid results even though the same optimization method could be used.

Examples of applications from other fields are robots and computer graphics. For humanoid robots the control strategies could be based on optimized movement patterns, even though the control demands real time evaluation. In computer graphics, the main application would be to derive human-like movements, where realistic forces and movements can be synthesized – if and when desired.

4.4. Individual adaptation

To be able to make conclusions on an individual basis, improved methods to define detailed mechanical descriptions about muscle strength, stiffness and deformities are needed. There exist methods to measure muscle strength of the lower extremities at joint level (Örtqvist *et al.* 2007). However, since deformities are common within possible subject groups it would be useful to have the ability to determine single muscle's properties in terms of attachment points and paths such that moment arms and muscle-tendon lengths can be determined. Very accurate methods have been developed where subject specific data are collected using Magnetic Resonance Images (MRI) (Arnold *et al.* 2000). The usage of such methods would make possible the consideration of subject specific deformities and muscle architectures. This information can be input to the existing model, allowing possible outcome of planned surgeries to be studied.

The collection of more data will require extra time at the clinical assessments. This means that in practice mostly generic data would be used, but with important individual modifications when subject specific measurements are available.

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