Analysis of locomotion in the horse using computer aided engineering software

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ABSTRACT

Locomotion of the horse is simulated using a model based on rigid-body dynamics. The equations of motion are generated and solved by a general-purpose Computer Aided Engineering software package [1]. When parameters obtained from experiments on a group of five ponies were fed into the model, typical in vivo behaviour of the equine locomotor system could be reproduced.

INTRODUCTION

Animal locomotion has been a subject of scientific investigations since the development of cinematography at the end of the 19th century [2]. During that period, Braune and Fischer [3] were the first to apply Newton's laws of dynamics to parts of the human musculoskeletal system. Further developments in this field have resulted in elaborate mathematical models in which biomechanics and muscle physiology have become thoroughly integrated. Using such models, it has become possible to predict optimal control strategies required for simple movements [4]. Similar success however, has not been obtained in the field of locomotion studies. The development of realistic locomotion models has always been frustrated by the huge amount of effort required for the proper mathematical formulation of even a simple model of the human musculoskeletal system.

The mathematical complexity of models of the locomotor system is a consequence of the essential non-linear nature of the equations of dynamics describing a system in which large relative movements occur. In contrast to the successful application of finite element methods in fluid dynamics and structural mechanics, true general-purpose numerical tools for model development and simulation in rigid-body dynamics have only recently become available.

This paper describes an application of the DADS rigid-body package [1] for analysis of locomotion in the horse. An important subject of study in equine locomotion research is the magnitude and distribution of forces inside the body, as it is generally assumed that overloading of joints, ligaments and tendons is one of the main causes of acute and chronic injuries in equestrian sports. Estimates of these forces have been obtained by quasi-static analysis [5] or by direct measurements on laboratory animals [6]. These methods however, lack the ability to predict the effect of different conditions and model properties on the behaviour of

the locomotor system. For this reason, it is desirable to develop a biomechanical model of the horse which can be used to simulate the behaviour of the musculoskeletal system under varying circumstances, including the extreme loading conditions that occur in top-level equestrian sports.

SIMULATION SOFTWARE

Newton's equations of motion for a system of linked rigid bodies [7] may be written as:

$$\begin{aligned} M\ddot{q} &= Q_e(q, \dot{q}, t) + Q_i(q, \dot{q}, t) + Q_c & (1) \\ \Phi(q, t) &= 0 & (2) \end{aligned}$$

The vector q of generalized coordinates contains the positions and orientations of all rigid bodies in the system. M is the corresponding generalized mass matrix. The generalized forces Q have been subdivided into external forces Q_e (gravity and ground reaction forces), internal forces Q_i (muscles and ligaments) and constraint forces Q_c . Constraint forces are required to make the movements satisfy the algebraic constraint relations (2), that represent the interdependence between movement of different bodies, for instance when two bones are connected by a joint. In case of a joint constraint, the net sum of joint contact force and joint ligament forces, responsible for maintaining joint contact, is one of the constraint forces.

The DADS package [1] builds the equations of motion from a high-level model description created by an interactive preprocessor. The unknowns q and Q_c are then solved from this system of coupled differential and algebraic equations by a special numerical method [7]. The package is especially suitable for biomechanical modelling, because user-written subroutines can be linked to the main analysis code. This feature was used to incorporate control models for skeletal muscles, including their curvilinear geometry, and the viscoelastic and frictional properties of the interface between hoof and ground.

HORSE MODEL

The equine body is represented by 25 rigid segments, connected by 22 hinge joints. In the living animal, movements are caused by well-coordinated actions of many muscles. This complexity is undesirable in developing a simulation model, because there are too many unknown parameters. For this reason a strategy of stepwise refinement was adopted. Initially, the kinematics of the proximal joints are prescribed by

Fig. 1. The 25 segments of the horse model and the muscles stabilizing the distal joints of the limbs.

time-dependent constraint equations (2), while the movements in the remaining joints and of the body as a whole are actually simulated. In each hindlimb, the three most distal joints are controlled by six, and in the forelimb two distal joints are controlled by five muscles. The structure of the model is shown in Fig. 1.

Kinematic data were obtained by cinematographic analysis of movement in five ponies. In the same group of animals, the contractions of the muscles included in the model were deduced from in vivo tendon strain recordings using implanted mercury-in-silastic strain transducers. The forces developed by these muscles could be modelled by a contractile element in series with a nonlinear spring representing the tendon. Tendon properties, inertial properties of the body segments, joint rotation centres and muscle geometry data were obtained by post-mortem measurements in the same animals. These data will be combined in a model representing the typical characteristics of the equine locomotor system.

RESULTS AND DISCUSSION

The simulation software described above was implemented on an Apollo DN4000 workstation, using the DADS software package (version 5.0). Normal walking was simulated, using kinematic data of the proximal joints and tendon strain recordings from a normal walking pony as driving input for the model. Fig. 2 shows the simulated movements in the distal part of the right forelimb during the stance phase, and the corresponding tendon forces. Both movements and forces resemble observations in live animals. During the development of this model, much insight into the functioning of the locomotor system was gained. In particular, the role of polyarticular muscles and ligaments in the equine limbs was better understood.

An important advantage of a simulation model is the availability of all mechanical variables in the system for measurements, whereas in vivo measurement methods can only supply information about a limited number of structures that are accessible for instrumentation [6]. During the development phase however, direct measurements are necessary to provide input for the model and for validation of the results of simulations. After successful validation, the model will be able to replace the laboratory animal in many cases.

Fig. 2. Simulated forces in the four flexor tendons in the forelimb during normal walking (a) and the movements of the forelimb during this time interval (b).

REFERENCES

- [1] DADS (Dynamic Analysis and Design System), Computer Aided Design Software Inc., Oakdale, Iowa.
- [2] Muybridge, E. (1899) *Animals in Motion*, London.
- [3] Braune, W. and Fischer, O. (1895-1900) *Der Gang des Menschen*. Abhandl. d. Math. Phys. Cl. d. Kön. Sächs. Ges. d. Wiss. 21, 25, 26, 28.
- [4] Hatze, H. (1976) The complete optimization of a human motion. *Math. Biosci.* 28:99-135.
- [5] Schryver, H.F., Bartel, D.L., Langrana, N. and Lowe, J.E. (1978) Locomotion in the horse: kinematics and external and internal forces in the walk and trot. *Am. J. Vet. Res.* 39:1728-1733.
- [6] Riemersma, D.J., Schamhardt, H.C., Hartman, W. and Lammertink, J. (1988) Kinetics and kinematics of the equine hindlimb I: in vivo tendon loads and force plate measurements. *Am. J. Vet. Res.*, in press.
- [7] Mani, N.K., Haug, E.J. and Atkinson, K.E. (1985) Application of singular value decomposition for analysis of mechanical system dynamics. *J. Mech. Transm. Autom. in Des.* 107:82-87.

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