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Short communication

A method of calculating physiologically relevant joint reaction forces during forward dynamic simulations of movement from an existing knee model

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Abstract

In the commonly used SIMM software, which includes a complete musculoskeletal model of the lower limbs, the reaction forces at the knee are computed. These reaction forces represent the bone-on-bone contact forces and the soft tissue forces (e.g. ligaments) other than muscles acting at the joint. In the knee model integrated into this software, a patellotibial joint rather than a patellofemoral joint is defined, and a force acting along the direction of the patellar ligament is not included. Although this knee model results in valid kinematics and muscle moment arms, the reaction forces at the knee calculated do not represent physiologic knee joint reaction forces. Hence our objectives were to develop a method of calculating physiologic knee joint reaction forces using the knee model incorporated into the SIMM software and to demonstrate the differences in the forces returned by SIMM and the physiologic forces in an example. Our method converts the anatomically fictional patellotibial joint into a patellofemoral joint and computes the force in an inextensible patellar ligament. In our example, the rectus femoris was fully excited isometrically, with the knee and hip flexed to 90°. The resulting SIMM tibiofemoral joint reaction force was primarily shear, because the quadriceps force was applied to the tibia via the fictional patellotibial joint. In contrast the physiologic tibiofemoral joint reaction force was primarily compression, because the quadriceps force was applied through the patellar ligament. This result illustrates that the physiologic knee joint reaction forces are profoundly different than the forces returned by SIMM. However physiologic knee joint reaction forces can be computed with postprocessing of SIMM results.

Keywords: Knee; Simulation; Movement; Forward dynamic; Musculoskeletal; Joint reaction force; SIMM

1. Introduction

A variety of computational programs exist that facilitate the simulation and analysis of musculoskeletal dynamics. One widely used program, SIMM (MusculoGraphics, Evanston, IL, USA), has been utilized in over 50 published studies, from analyses of gait and pedaling in humans (Piazza and Delp, 1996; Neptune et al., 2000; Arnold and Delp, 2001; Zajac et al., 2002; Thelen and Anderson, 2006), to modeling the equine forelimb (Swanstrom et al., 2005). A valuable feature of this software is the calculation of joint reaction forces, which represent bone-on-bone contact forces and soft tissue forces other than muscles acting at the joint. Knowledge of these forces has applications in designing possible rehabilitation methods (Neptune and Kautz, 2000), estimating the load carried by soft tissues (Lloyd and Buchanan, 1996), and in the design of prosthetics (Delp et al., 1996). However, because the knee joint model defined in the standard two-dimensional model of the lower limbs incorporated into SIMM includes a fictitious patellotibial joint and does not include the patellar ligament, the knee joint reaction forces returned by SIMM are not physiologic. Hence, the objectives of our study were to develop a method of calculating physiologic knee joint reaction forces, using the existing planar knee model incorporated in SIMM, and to demonstrate the differences in the knee joint reaction forces returned by

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SIMM and the physiologic knee joint reaction forces through an example.

2. Methods

The two-dimensional SIMM model of the lower limbs was originally developed by Delp et al. (1990). The knee model consisted of a tibiofemoral and a patellotibial joint. In the tibiofemoral joint, translations of the tibial origin in the sagittal plane were coupled to knee flexion angle. In the patellotibial joint, sagittal translations and the rotation of the patella relative to the tibia were prescribed functions of knee flexion angle. These functions were determined by assuming a patellar ligament of constant length and using experimental measures of patellar ligament rotation and patellar rotation (Delp et al., 1990), based on data from van Eijden et al. (1985). In the actual knee, there is no articulation between the tibia and patella, but by defining this joint in SIMM, the motion of the patella relative to the tibia was controlled, and quadriceps moment arms that corresponded with experimental data were found. No patellar ligament was modeled. With the knee defined this way, the force generated by the quadriceps is transmitted to the tibia via a patellotibial joint reaction force and moment (Fig. 1), instead of by the patellar ligament. Joint reaction forces represent bone-on-bone contact forces and soft tissue forces other than muscles acting at the joint. Between the tibia and patella, however, there is no anatomical structure that is capable of transmitting the patellotibial joint reaction force and moment. The patellar ligament is not such a structure because it is capable of transmitting a force only along its length, and is not capable of transmitting a moment. Hence, the patellotibial joint reaction force and moment have no physiological equivalent. Furthermore, the tibiofemoral joint reaction force calculated by SIMM is not physiologic, because it is affected by the anatomically fictional patellotibial joint reaction force. No patellofemoral joint reaction force is calculated.

To calculate physiologic tibiofemoral and patellofemoral joint reaction forces, the anatomically fictional patellotibial joint reaction force was removed, and a force acting along the direction of the patellar ligament was added. Because the length of the patellar ligament does not change, the patellar ligament force does no work on the system, and so does not affect the system kinetics. In Kane dynamics, which is the methodology used by SIMM, the patellar ligament force is noncontributing, meaning that it does not contribute to the generalized active forces that drive the system, but rather is a result of contributing forces such as gravity and muscle forces (Kane and Levinson, 1985). In classical dynamics terms, the sum of the forces and the sum of the moments on each segment remains the same; only the distribution of the joint reaction loads is changed. The significance of this is that replacing the moment applied by the patellotibial joint reaction loading with an equal moment resulting from the patellar ligament does not affect the equations of motion, and hence does not affect the muscle forces required to produce a given motion.

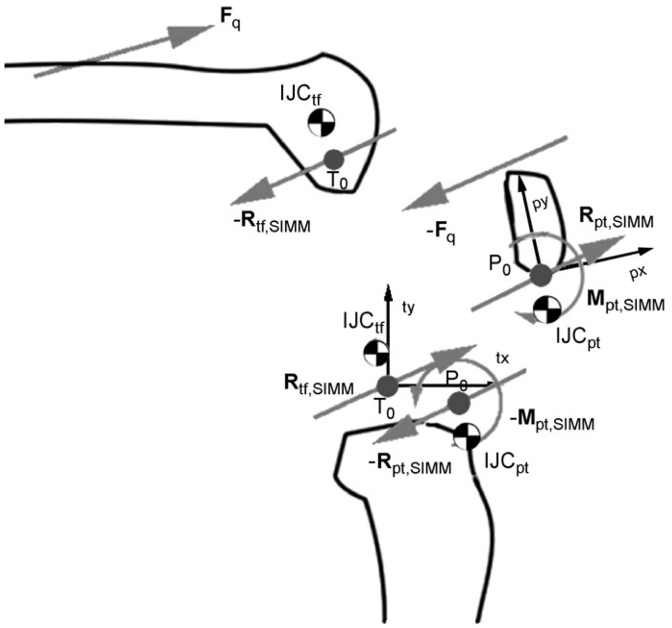

Fig. 1. Free body diagram of SIMM knee model. T_0 and P_0 are the tibial and patellar coordinate system origins. IJC_{tf} and IJC_{pt} are the instantaneous tibiofemoral and patellotibial joint centers, respectively. The force generated by the quadriceps $\mathbf{F}_q$ is transmitted to the tibia via a patellotibial joint reaction force $\mathbf{R}_{pt,SIMM}$ and moment $\mathbf{M}_{pt,SIMM}$ applied at P_0. $\mathbf{R}_{pt,SIMM}$ is the tibiofemoral joint reaction force.

The magnitude of the patellar ligament force was set so that the resulting moment about the axis of knee rotation equals that of the sum of the moments produced by the quadriceps muscle forces:

$$|\mathbf{F}_{pl}| = \frac{\sum_{i=1}^{4} |\mathbf{F}_{qi}| A_{qi}}{A_{pl}}, \tag{1}$$

where $\mathbf{F}_{pl}$ is the force applied by the patellar ligament, $\mathbf{F}_{qi}$ is one of the four quadriceps muscle forces acting in the sagittal plane, A_{qi} is the corresponding muscle moment arm, and A_{pl} is the patellar ligament moment arm.

Muscle moment arms were calculated using the partial velocity method described by Delp (1990). In this method, the partial velocity of the first via point not fixed in the segment from which the muscle originates, in this case the femur, is dotted with a unit vector in the direction of the muscle line of action. The line of action is the line connecting the last via point defined in the body of origin with the first via point not defined in the femur. For muscles crossing two joints, such as the quadriceps, which in this model cross both the tibiofemoral and patellotibial joints, partial velocities are summed over both joints:

$$A_{qi} = ({}^{\mathrm{F}}\mathbf{PV}^{P_{mi}} + {}^{\mathrm{T}}\mathbf{PV}^{P_{mi}}) \bullet \mathbf{V}_i \tag{2}$$

where ${}^{\mathrm{F}}\mathbf{PV}^{P_{mi}}$ and ${}^{\mathrm{T}}\mathbf{PV}^{P_{mi}}$ are the partial velocities of via point P_{mi} in the femur and tibia coordinate systems, respectively, and $\mathbf{V}_i$ is a unit vector in the direction of the muscle's line of action.

The patellar ligament moment arm was calculated using a cross product method:

$$A_{pl} = |\mathbf{R}_{pl} \times \mathbf{V}_{pl}|, \tag{3}$$

where $\mathbf{R}_{pl}$ is a vector from the tibiofemoral instantaneous joint center to the patellar ligament insertion point, and $\mathbf{V}_{pl}$ is a unit vector in the direction of the patellar ligament. The tibiofemoral instantaneous joint center is the point in the tibia local coordinate system that has a partial velocity of 0, relative to the femur.

To find the direction of the patellar ligament, the location of the insertion point used to develop the SIMM patellotibial joint had to be determined. This point is not explicitly specified in the literature, and so was found using an optimization process. Assuming a constant patellar ligament length of 55 mm, which is recorded in the SIMM joint file, the insertion of the patellar ligament was found that minimized the root mean squared error in the length of the patellar ligament over the full range of knee flexion. This point was found to be at 32.10, −74.94 mm in the tibial coordinate system, with a root mean squared error of 0.12 mm.

With the patellar ligament force determined, physiologic patellofemoral and tibiofemoral joint reaction forces could then be calculated (Fig. 2). The physiologic patellofemoral joint reaction force is the patellofemoral intersegmental force minus the quadriceps muscle forces and the patellar ligament force. Intersegmental forces are a result of segment accelerations and of environmental forces (Zajac et al., 2002). Joint reaction forces are equal to the difference between the intersegmental forces and the muscle forces, and represent bone-on-bone contact forces and soft tissue forces other than muscles. The patellofemoral intersegmental force is a result of the patella's weight and acceleration. Because neither the patella's weight nor acceleration is affected by adding the patellar ligament, the patellofemoral intersegmental force is equal to the patellotibial

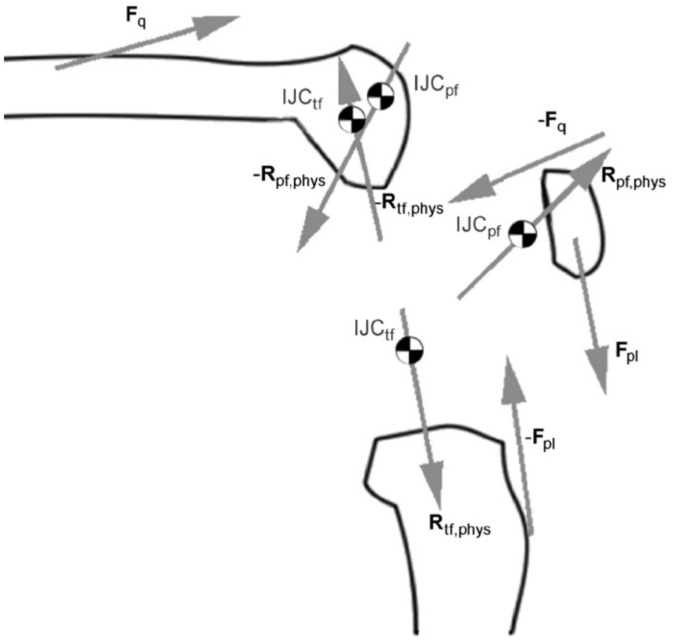

Fig. 2. Free body diagram of the physiologic knee model. IJC_{pf} is the newly defined instantaneous patellofemoral joint center. $\mathbf{F}_{pl}$ is the force carried by the patellar ligament. $\mathbf{R}_{pf,phys}$ and $\mathbf{R}_{tf,phys}$ are the new physiologic patellofemoral and tibiofemoral joint reaction forces, respectively.

intersegmental force calculated by SIMM:

$$\mathbf{I}_{pf} = \mathbf{I}_{pt} = \mathbf{R}_{pt,SIMM} + \sum_{i=1}^{4} \mathbf{F}_{qi}, \tag{4}$$

where $\mathbf{I}_{pf}$ and $\mathbf{I}_{pt}$ are the patellofemoral and patellotibial intersegmental forces, respectively, and $\mathbf{R}_{pt,SIMM}$ is the patellotibial joint reaction force returned by SIMM. The physiologic patellofemoral joint reaction force $\mathbf{R}_{pf,phys}$ is then equal to

$$\mathbf{R}_{pf,phys} = \mathbf{I}_{pf} - \sum_{i=1}^{4} \mathbf{F}_{qi} - \mathbf{F}_{pl} = \mathbf{R}_{pt,SIMM} - \mathbf{F}_{pl}. \tag{5}$$

To calculate a physiologic tibiofemoral joint reaction force $\mathbf{R}_{tf,phys}$, the anatomically fictional patellotibial joint reaction force is removed, and the patellar ligament force is added:

$$\mathbf{R}_{tf,phys} = \mathbf{R}_{tf,SIMM} - \mathbf{R}_{pt,SIMM} + \mathbf{F}_{pl}, \tag{6}$$

where $\mathbf{R}_{tf,SIMM}$ is the tibiofemoral joint reaction force calculated by SIMM. The coordinate system used in these calculations does not matter, as long as the same coordinate system is used consistently for all forces.

The above method was demonstrated for an isometric example, with the right knee and hip both flexed to 90°. Only the rectus femoris muscle was modeled, and was fully excited. The magnitude and direction of the physiologic tibiofemoral and patellofemoral joint reaction forces were compared to the tibiofemoral and patellotibial joint reaction forces returned by SIMM. Tibiofemoral joint reaction forces were reported in the tibial coordinate system, while patellofemoral and patellotibial joint reaction forces were reported in the patellar coordinate system (Fig. 1). At the tibiofemoral joint, the normal and shear forces are in the direction of the tibia's *ty*- and *tx*-axes, respectively. At the patellofemoral joint, the normal and shear forces are directed in the *px*- and *py*-axes, respectively.

3. Results

The isometric rectus femoris muscle force when fully excited was 355 N. The SIMM tibiofemoral joint reaction force was primarily a shear force, with *tx* and *ty* components of 352 and −4 N, respectively (Fig. 3). In contrast, the physiologic tibiofemoral joint reaction force was primarily compressive, with *tx*- and *ty*-components of 0.1 and −186 N, respectively. The *px*- and *py*-components of the SIMM patellotibial joint reaction force were 322 and −149 N, respectively, while the *px*- and *py*-components of the physiologic patellofemoral joint reaction force were 389 and 200 N, respectively.

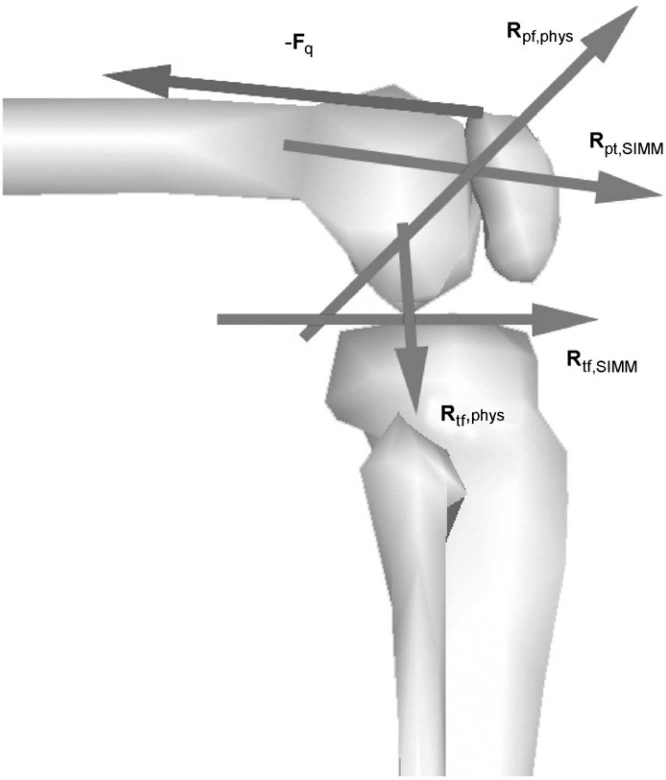

Fig. 3. Visualization of reaction force vectors acting at the knee in our static example calculation. $\mathbf{R}_{pf,phys}$ and $\mathbf{R}_{pt,SIMM}$ act on the femur. $\mathbf{R}_{tf,SIMM}$ and $\mathbf{R}_{tf,phys}$ act on the tibia. $\mathbf{F}_q$ is the force generated by the rectus femoris.

4. Discussion

The objectives of the work reported in this paper were to develop a method of obtaining physiologic knee joint reaction forces from data generated using an existing SIMM model and to demonstrate the differences between the SIMM knee joint reaction forces and the physiologic knee joint reaction forces through a simple example. The first objective was accomplished by removing the anatomically fictional patellotibial joint reaction force, and by applying a force through the inextensible patellar ligament. The results from our example indicated that applying a force through the patellar ligament resulted in a physiologic tibiofemoral joint reaction force that differed substantially from its SIMM counterpart. The SIMM tibiofemoral joint reaction force was primarily shear and nearly equal and opposite to the rectus femoris muscle force. The quadriceps force is applied to the tibia via the patellotibial joint. At 90° of knee flexion, the quadriceps force was directed nearly perpendicular to the tibia's long axis, so that the shear component of the SIMM tibiofemoral joint reaction force was nearly equal to the force generated by the quadriceps. Because the quadriceps muscles are capable of generating considerable force, this amount of shear is clearly not representative of actual knee loading. By applying the quadriceps force through the patellar ligament, our calculation of the physiologic tibiofemoral joint reaction force was mostly compressive with only a slight shear component. Qualitatively, these results are similar to tibiofemoral joint reaction forces calculated from other simulations, which report high compressive forces and comparatively small shear forces during activities such as walking and stair climbing (Taylor et al., 2004; Komistek et al., 2005).

The physiologic patellofemoral joint reaction force also differed substantially from the patellotibial force calculated by SIMM. Applying the patellar ligament force resulted in a higher compressive component, and a shear component in the opposite direction.

In past studies some researchers may not have been aware of the discrepancy between the joint reaction forces calculated by SIMM and physiologic knee joint reaction forces, and may have incorrectly interpreted knee joint loading. Although the correction to the SIMM knee model reported herein requires an additional processing step, it can be used to correct past results without repeating the simulation, which can be a lengthy process in the case of forward dynamic simulations. The required data are the muscle forces of the quadriceps, the hip and knee angles, the SIMM knee joint reaction forces, and the patellotibial and tibiofemoral kinematic functions given in the joint file. The calculations for a dynamic case would not change, because forces resulting from segment accelerations are included in the SIMM calculated joint reaction forces. Future improvements would be either modifications to the SIMM knee model or to the C code created by SIMM, so that no additional processing is required.

Conflict of interest

No conflicts.

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