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A real-time topography of maximum contact pressure distribution at medial tibiofemoral knee implant during gait: Application to knee rehabilitation

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ABSTRACT

Knee contact pressure is a crucial factor in the knee rehabilitation programs. Although contact pressure can be estimated using finite element analysis, this approach is generally time-consuming and does not satisfy the real-time requirements of a clinical set-up. Therefore, a real-time surrogate method to estimate the contact pressure would be advantageous.

This study implemented a novel computational framework using wavelet time delay neural network (WTDNN) to provide a real-time estimation of contact pressure at the medial tibiofemoral interface of a knee implant. For a number of experimental gait trials, joint kinematics/kinetics and the resultant contact pressure were computed through multi-body dynamic and explicit finite element analyses to establish a training database for the proposed WTDNN. The trained network was then tested by predicting the maximum contact pressure at the medial tibiofemoral knee implant for two different knee rehabilitation patterns; "*medial thrust*" and "*trunk sway*". WTDNN predictions were compared against the calculations from an explicit finite element analysis (gold standard).

Results showed that the proposed WTDNN could accurately calculate the maximum contact pressure at the medial tibiofemoral knee implant for *medial thrust* ($\overline{RMSE}=1.7$ MPa, $\overline{NRMSE}=6.2\%$ and $\overline{\rho}=0.98$) and *trunk sway* ($\overline{RMSE}=2.6$ MPa, $\overline{NRMSE}=9.3\%$, $\overline{\rho}=0.96$) much faster than the finite element method. The proposed methodology could therefore serve as a cost-effective surrogate model to provide real-time evaluation of the gait retraining programs in terms of the resultant maximum contact pressures.

1. Introduction

Growing prevalence of knee osteoarthritis (OA) as the main cause of knee arthroplasty on one hand and cost, risk and complications of the surgery on the other hand have led to the significant development of non-surgical gait modifications [1–7]. Gait modification aims to alter walking patterns to decrease knee joint loading through minor changes in gait kinematics. Similarly the load reduction on the artificial knee joint can also be achieved through gait modifications and rehabilitation strategies to minimize wear and prolong the clinical life time of the prosthesis. A number of gait modifications have been reported in the literature to reduce knee joint loading [8–12]. These modification strategies have been mainly designed to offload the knee joint. However, offloading gait interventions may reduce knee contact area, leading to an adverse increase in contact pressure on the joint bearing surfaces. Therefore an off-loading strategy may not be very beneficial and can even be detrimental to the knee joint [13]. Therefore the resultant contact pressure on the articulating surfaces should be considered in clinical implementation of rehabilitation programs.

Finite element analysis (FEA) is a powerful computational technique to calculate contact pressure [14–17]. However this approach is highly time-demanding and computationally expensive. Therefore, FEA is mainly used as a *post-processing* stage for multi-body dynamic analysis to provide tissue-level information. In fact, the available FEA methods do not satisfy the necessity of real-time calculation in a clinical setup. In clinical rehabilitation, patients should be trained to internalize the rehabilitation strategy as their daily walking patterns. Therefore, real-time evaluation of contact pressure benefits the clinical implementation of rehabilitation programs, for example to investigate the effect of a rehabilitation strategy on the knee joint contact pressure.

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Artificial intelligence is a relatively new method that has been used in various fields of biomechanics as a real-time surrogate model [18–21]. An artificial intelligent network consists of a number of processor units (neurons) that are densely connected to each other via numeric weights. Once a set of inputs and resultant outputs are presented to the network; the causal relationships between inputs and outputs would be captured and stored in numeric weights. Thus, the network "learns" the interaction between inputs and outputs. Given a "new" set of inputs that has not seen by the network before, the trained neural network (surrogate model) can generalize the relationship to produce the associated output and release the necessity of running the original model and repetition of time consuming calculations [22]. In particular, neural networks have been jointly used with finite element simulation in a variety of biomechanics studies such as load estimation [23–25] and bone remodeling [26,27]. Study of Lu et al. to best of our knowledge is the only study that has used the aforementioned approach to predict the contact pressure [28]. Lu et al. predicted the spatial distribution of contact stress at medial tibia cartilage for a simplified contact model with 400 structural elements. A one-by-one mapping was developed from the three dimensional force data space into the resultant contact stress through a time delay neural network (TDNN). However, their proposed TDNN had a fairly large structure (1200 inputs, 400 outputs and 280 hidden neurons) for a simplified contact model which limits its practical function in realistic application. In fact due to the one-by-one mapping set-up, the proposed TDNN structure cannot be used for a more realistic contact model since increasing the number of elements in the model would increase the number of inputs and outputs resulting in a more complicated structure which requires further number of training data sets. On the other hand, in clinical applications, resultant *maximum contact pressures* are mainly of interests. In this case, the time history of spatial contact pressure distribution is not required. Instead, the maximum contact pressures and the corresponding contact regions that occur over the entire gait cycle should be focused.

The aims of this study were to (1) propose a novel computational framework to predict the distribution of "maximum" contact pressure instead of "spatial" distribution through a simple cost-efficient neural network structure for a realistic contact model, and (2) demonstrate the advantages of the proposed approach in an application to provide a real-time evaluation of knee rehabilitation strategies in terms of maximum contact pressure and corresponding contact regions at the medial tibiofemoral knee implant.

2. Materials and methods

Artificial intelligent surrogates require a primary database to describe the "causal" interactions between inputs and outputs [29]. Therefore, a number of gait trials, obtained from literature, were imported to multi-body dynamic (MBD) analysis to estimate knee joint kinematics and kinetics. Resultant kinematics and forces, from MBD analysis, were then used as boundary conditions and load profiles in finite element analysis (FEA) to calculate the contact pressure distribution. A data matrix constructed from knee kinematics/kinetics (inputs) and contact pressures (outputs) served as the required training database for the proposed surrogate model. The overall ability of this surrogate was then tested by predicting the contact pressure for a number of rehabilitation gait trials. It should be pointed out that FEA was used for a twofold purpose: first, to construct the training database and second, as a gold standard to compare with the surrogate predictions. Fig. 1 shows an overview of the methodology used in this study.

2.1. Database

Experimental gait trials of four subjects, implanted with unilateral knee prosthesis (three male and one female, height: 168.3 ± 2.6 cm; mass: 69.2 ± 6.2 kg), were obtained from a previously published repository [https://simtk.org/home/kneeloads; accessed on June 2013]. All subjects were implanted with sensor-based knee prostheses that have been specifically manufactured for in vivo measurement of knee joint forces [30]. The database included three dimensional ground reaction

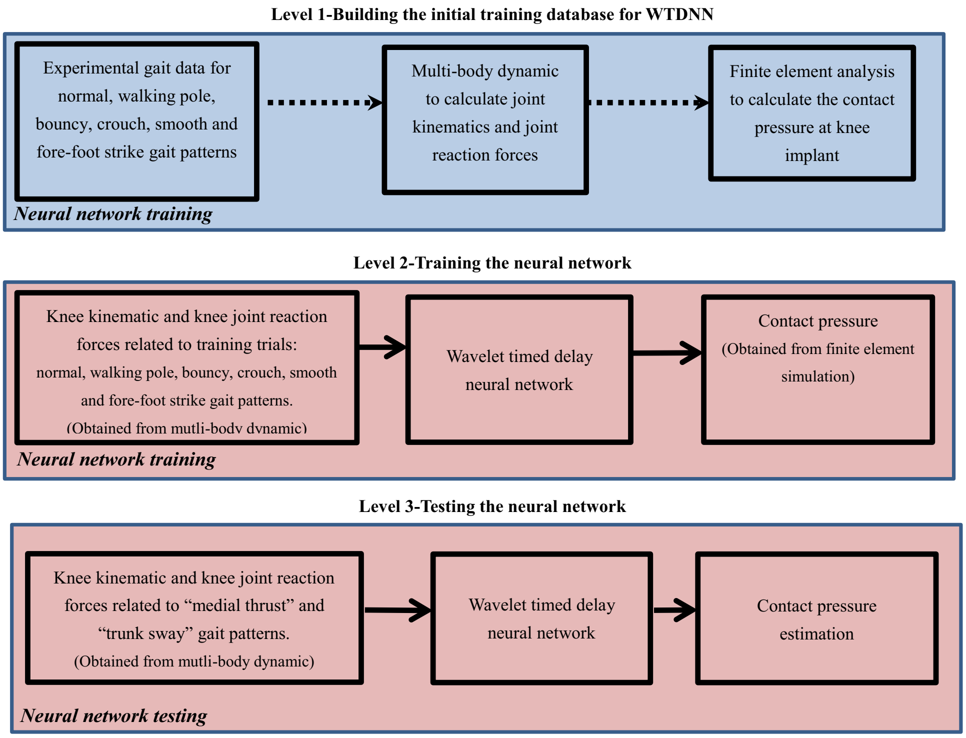

Fig. 1. Schematic description of the proposed methodology.