PREDICTION OF CONTACT AND MUSCLE FORCES FROM KINEMATICS DATA ONLY - APPLICATION TO 3D SIMULATION OF CLIMBING MOTION

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Note to the scientific committee:

This paper is a reprise of the second part of a paper already published by the same authors in the book “The Science of Climbing and Mountaineering”, L. Seifert, P. Wolf and A. Schweizer (editors). The authors thought it will be interesting to present it to the audience of the IRCRA 2018 conference. The present submission outlines methodology and results. The details of the content remain in the book version.

Abstract

Whether on flat ground or a vertical wall, locomotion relies on a combination of contact forces and muscle torques to propel the center of mass. In Biomechanics, estimation of these muscle forces plays a central role in the analysis of dynamics of motion but requires costly force sensors to solve for the Inverse Dynamics problem. We present here a study to estimate contact forces and muscle torques directly from kinematics data without force sensors. The methodology computes the force torques by optimization with the assumption that the climber tends to minimize the repartition of its effort during performance. We evaluate the results on a 3 meters high climbing wall equipped with force sensors for comparison to ground truth. Results showed that an estimation of force contacts and muscle torques from optical data only can be achieved with an accuracy of 20 to 35% of the body weight. From this methodology, we derive a software simulation of climbing motion using a 3D biomechanical model of the climber.

Key-words : Motion Analysis; Inverse Dynamics; Contact Forces; 3D Simulation.

Résumé

Que ce soit sur un sol plat ou sur un mur vertical, la locomotion repose sur une combinaison de forces de contact et de couples musculaires pour propulser le centre de masse. En biomécanique, l'estimation de ces forces musculaires joue un rôle central dans l'analyse de la dynamique du mouvement, mais nécessite des capteurs de force coûteux pour résoudre le problème de la dynamique inverse. Nous présentons ici une étude pour estimer les forces de contact et les couples musculaires directement à partir de données cinématiques sans capteurs de force. La méthodologie calcule les couples de force par optimisation en supposant que le grimpeur a tendance à minimiser la répartition de son effort pendant la performance. Nous évaluons les résultats sur un mur d'escalade de 3 mètres de haut équipé de capteurs de force pour la comparaison avec la vérité terrain. Les résultats ont montré qu'une estimation des contacts de force et des couples musculaires à partir de données optiques seulement peut être obtenue avec une précision entre 20 et 35% du poids corporel. A partir de cette méthodologie, nous dérivons une simulation de mouvement en escalade à l'aide d'un modèle biomécanique 3D simplifié du grimpeur.

Mots-clef : Analyse de Mouvement; Dynamique Inverse; Forces de contact; Simulation 3D.

Introduction

To study the dynamics of human motion, the regular methodology consists in combining measurement of the kinematics of the motion with measurement of ground reaction forces using force plates. With a model of masses and inertia of the body part, muscle torques are computed using an Inverse Dynamics formulation. This scenario is more difficult to transpose to climbing as it is challenging to equip the holds with force sensors. The study presented here evaluates to what extent muscle torques and contact forces on hold could be automatically predicted from optical data only, without the use of force sensors.

Methods

Having no measurement of contact forces left unsolved degrees of freedom in the resolution of the Inverse Dynamics problem. The value of force contacts can be directed linked to the value of muscle torques using the standard Newtonian equation of laws of motion. The prediction of force contacts has thus been cast as an optimization problem on muscle torques with the assumption that the climber tends to choose the lowest expenditure of energy and thus minimize the sum of torques. For experimental validation, a 3m high climbing wall has been built with a negative slope of 4 degrees and 6 holds equipped with force sensors (AMTI).

Figure 1. – Climbing wall equipped with force sensors

Nine climbers have participated in the data capture process. Two beginners, two intermediate climbers, and five expert climbers have participated in the experiment. The beginners were men climbing for the first or for the second time. The intermediate climbers were women climbing at a level between 5.10d and 5.11b. The expert climbers were men with best redpoint ascent from 5.13a to 5.14a. A total of 172 recordings have been captured. In addition to force sensors, kinematics data have been recorded using a motion capture system (OptiTrack) and a set of markers. The motion capture data are used as input to compute the contact forces by optimization. This estimation is compared to contact forces measured on the sensors. To simplify computation, we approximate contacts as point contacts only and thus consider that only forces, and no torques, are applied at the contact. The holds are considered as plain grips concentrated at a single point of contact. After clean-up and data selection, we isolated 15 sequences of motion for the study.

We followed the same mathematical formulation as Robert et al. (2013). In this approach, the optimization process involves the choice of a set of weighting factors per joint. To obtain the force contacts value from the kinematic data only, Robert et al. (2013) derives a set of weighing factors for the internal torques from the literature. We compared this set of parameters with two other sets: one set of uniform weights and one set derived from maximal values recorded by the force sensors.

Results and discussion

The average quality of the contact force prediction is between 20 and 35% of the performer body weight. Results suggest that the choice of weights is specific to the activity as a uniform set of parameters provides better results than the parameters used in Robert et al. (2013) for a different task. This suggested investigating more specific parameters for optimization. To this end, we used the value of real contact forces measured by the sensor to perform a standard inverse dynamics computation on the performers' data. This provided the values of internal joint torques out of which we retained the maximal magnitude as an indicator of weighing factor. Like in Robert et al. (2013), the rationale is that larger maximal torques must correspond to smaller weighing factors to let the minimization produce solutions with increased internal torque values. This choice of parameters allows us to significantly improve the prediction of contact forces for one performer only, and does not yet generalize to parameters specific to climbing.

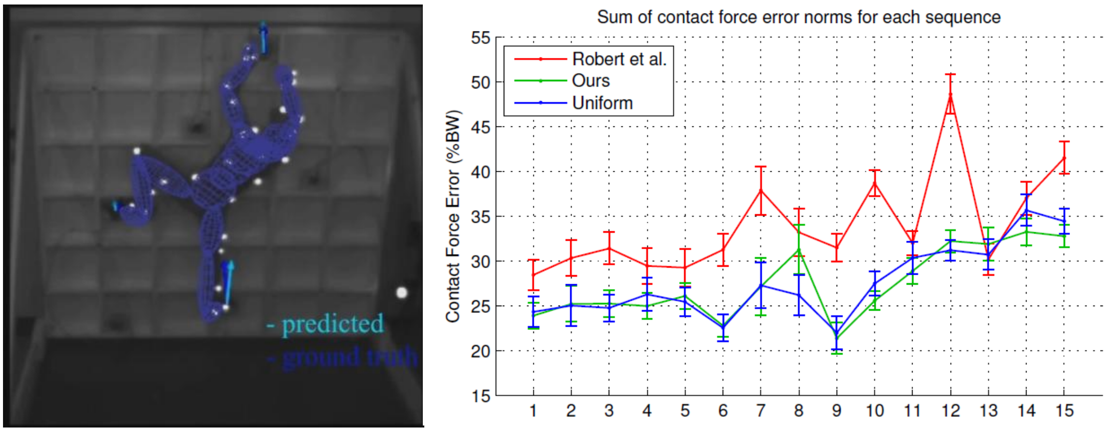

Figure 2 – Muscle torques prediction in % of body weight.

As a conclusion, this approach of computing contact forces from inverse dynamics cannot be considered a complete replacement of hardware force sensors obviously but could nevertheless provide insight on the torques distribution between body segments and as such being a support for training. In the next section, we present a way to make use of this technique to simulate 3D climbing motion on a bouldering wall. We compare this generated motion to the performance of a real subject.

Application to 3D simulation of climbing

The input to the simulation consists of a set of holds located on a wall and a discrete sequence of postures of an anthropomorphic mannequin using these holds to perform a complete climbing route. Motion planning is thus constrained as the interpolation between these poses. Between poses, the spatial interpolation follows a straightforward linear scheme for hand and foot positions using a cubic spline interpolation for the root joint position and a spherical interpolation for the orientation of the joints. The parameter left free is the timing of these interpolations, that is, how fast transitions between poses occur.

To solve for this free timing parameter and generate simulated motion, we apply here the hypothesis of optimal torque described in the previous section. Between poses, the transition duration is broken down into a set of 3 units whose individual time can vary. Along with the spatial interpolation between poses, duration values given to these segments create full body kinematic trajectories of the limbs, similar to virtual motion capture trials. Using the previously described method, contact forces and internal torques are automatically derived from the kinematic hypothesis. Among all the possible values of timing segments, an overall optimization thus selects the ones that correspond to the sum of least internal torques.

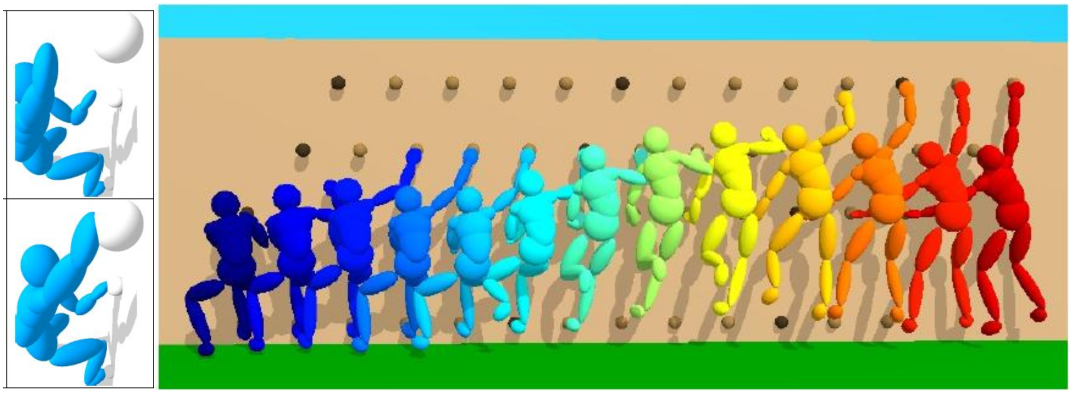

Figure 3 – 3D simulation of climbing motion

References

Robert, T., Causse, J., Monnier, G. (2013). Estimation of external contact loads using an inverse dynamics and optimization approach: General method and application to sit-to-stand maneuvers. Journal of biomechanics, 46(13), 2220-2227.

F. Quaine, L. Reveret, S. Courtemanche, P. Kry. Postural regulation and motion simulation in rock climbing. Ludovic Seifert; Peter Wolf; Andreas Schweizer. The science of climbing and mountaineering, Routledge, pp.111-128, 2017, Routledge Research in Sport and exercise Science, 2017.