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External Forces and Moments Prediction During Obstacle Crossing: Evaluation and Perspectives for Military Field Applications

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1. Introduction

Military missions involve physical activities that expose soldiers to musculoskeletal injuries. Analyzing these injury mechanisms requires precise Ground Reaction Forces and Moments (GRF&M) data to estimate internal loads, such as joint torques and muscle forces, through inverse dynamics and static optimization. Optimization-based algorithms using kinematic data and biomechanical models allow for GRF&M prediction without force plates. Such methods have been validated for diverse tasks like running, vertical jumping, and side-cutting (Skals et al., 2017). While applied in military research (Graham et al., 2025), these methods lack experimental validation for specific tasks like obstacle crossing. Such maneuvers require simultaneous contact from both hand and foot and are typically encountered in field environments (Carlton et al., 2014). This study compares two GRF&M prediction methods against experimental data. The first function minimizes reaction forces, while the second incorporates joint torque minimization to resolve the indeterminacy of simultaneous contacts.

2. Methods

2.1 Experimental data

Thirteen active-duty French soldiers (12M, 1F; 28±6 years, 1.77±0.05m, 77±9kg) participated to this study, which was approved by the national ethics committee (CPP n°2024-A02738-39). Five repetitions of obstacle crossing (1-m height) were performed. The technique used includes three phases: takeoff, hand and foot support on the obstacle, and a single-leg landing. Each participant was equipped with 48 reflective markers positioned on anatomical landmarks according to the International Society of Biomechanics recommendations. Marker trajectories were recorded at 200Hz using 26 Qualisys® optoelectronic cameras and pre-processed within Qualisys® Track Manager. Two force platforms (2000Hz) and an instrumented obstacle with two AMTI® force sensors (5000Hz) were used for GRF&M collection.

2.2 GRF&M prediction and analysis

The CusToM toolbox (Muller et al., 2019) was used for inverse kinematics and GRF&M prediction, using a whole-body biomechanical model with 38-degree-of-freedom (DoF). The following problem was solved frame-by-frame using sequential quadratic programming (SQP) optimization:

$$\min_{F} \alpha \times cost_1 + \beta \times cost_2$$

with,

$$cost_1 = \sum_{i=1}^{N_f} \left\| F_i \right\|^2 \text{ and } cost_2 = \sum_{j=1}^{N_{DoF}} \left\| \tau_j \right\|^2$$

$$s.t. \begin{cases} M(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) + \lambda + \boldsymbol{E} = \boldsymbol{0} \\ \forall i \in [1, Nf], \boldsymbol{F_i} < \boldsymbol{F_{i_{max}}} \end{cases}$$

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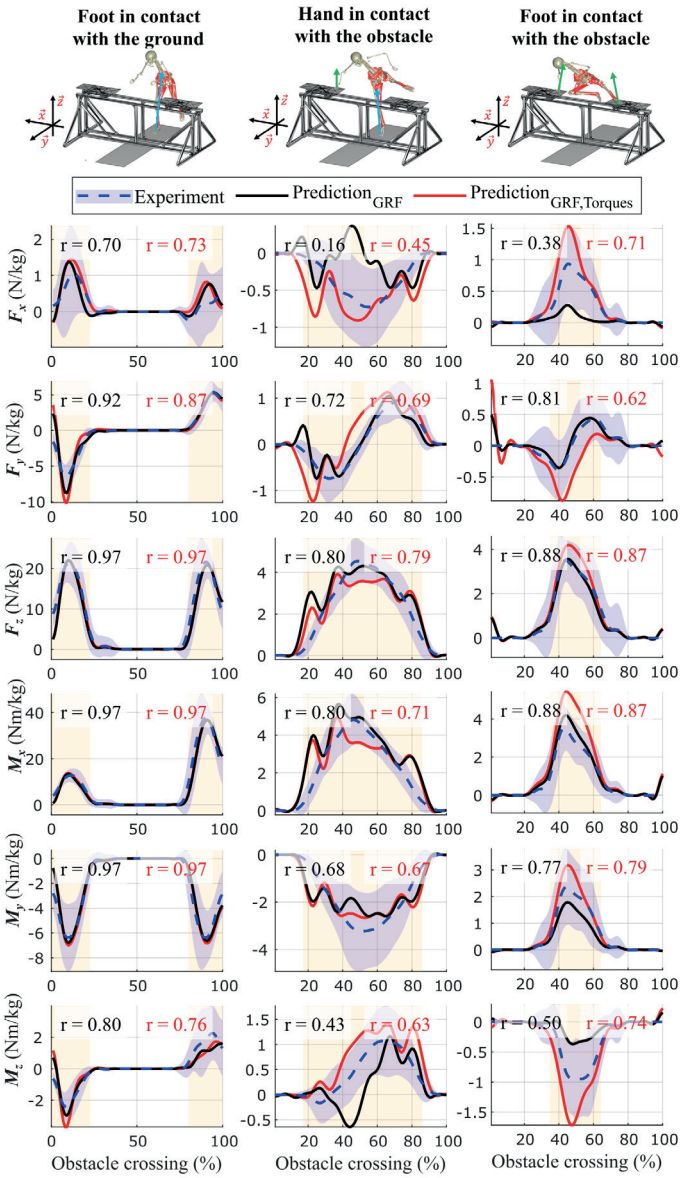

Figure 1. GRF&M for each contact. The orange-shaded area indicates the duration of contact.

Credit: A. Schuster

Where $M(\boldsymbol{q})$ is the inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is the centrifugal and Coriolis force vector, $\boldsymbol{G}(\boldsymbol{q})$ is the gravity vector, $\boldsymbol{\lambda}$ and $\boldsymbol{E}$ represent internal and external generalized force vectors, and $\boldsymbol{\tau}$ is the joint torque vector for each rotational DoF. The model incorporated $N_f = 14$ contact points per foot and 11 per hand, with force limits $\boldsymbol{F}_{i_{max}}$ set at 0.4 × body weight. Contact detection followed the methodology of Muller et al. (2020), based on point position and velocity relative to the surface. Activation thresholds were set at 0.05m for vertical position and 0.8m/s for velocity.

Two prediction methods were defined by modifying the cost function with $\alpha = 1, \beta = 0$ to minimize GRF (Pred_{GRF}), and $\alpha = 1, \beta = 1$ to minimize GRF and joint torques ($\text{Pred}_{GRF,\tau}$). They were evaluated by computing Pearson correlation coefficients (r) and relative Root Mean Square Errors (rRMSE) between measured GRF&M for each component.

3. Results and discussion

Results showed the highest agreement for vertical forces, with the highest r (Fig. 1) and lowest rRMSE across all contacts (Table 1). While $\text{Pred}_{GRF,\tau}$ improved lateral forces predictions ($\boldsymbol{F}_x$), the opposite occurred for Pred_{GRF} regarding antero-posterior forces ($\boldsymbol{F}_y$), especially for hand and foot obstacle contact. Regarding moments on the obstacle, $\text{Pred}_{GRF,\tau}$ showed better consistency for hand and foot transverse moments ($\boldsymbol{M}_z$), compared to Pred_{GRF}, while other components remained similar.

Discrepancies between predicted and experimental hand forces occurred at foot-strike, probably due to the initiation of foot-obstacle contact. Applying a specific weighting between the force and joint torque terms in the cost function could attenuate this effect. Stability during double support likely involves higher adduction joint torques at the hand and foot. Accounting these torques in the optimization improves the prediction of $\boldsymbol{F}_x$ and $\boldsymbol{M}_z$ but leads to decreased accuracy in the $\boldsymbol{F}_y$ component, particularly for the foot.

Table 1. Mean rRMSE(%) (±SD). Lower rRMSE values are highlighted in bold. Black: $Pred_{GRF}$; Red: $Pred_{GRF,\tau}$

	Foot in contact with the ground	Hand in contact with the obstacle	Foot in contact with the obstacle
$\boldsymbol{F}_x$	15,5±5,3 **15,3±4,6**	37,2±10,3 **32,3±7,9**	64,5±25,9 **37,3±16,4**
$\boldsymbol{F}_y$	**7,8±3,1** 9,7±3,8	**18,4±5,7** 20,9±4,8	**21,2±10,9** 41,6±19,6
$\boldsymbol{F}_z$	8,2±1,7 **7,7±2**	20,8±6,2 **20,2±4,8**	**16,1±7,5** 23,1±15,3
$\boldsymbol{M}_x$	6,5±1,4 **6,3±1,4**	**22,6±6,9** 23±5,9	**22,9±23,6** 38,7±29
$\boldsymbol{M}_y$	**8±1,7** 8,3±2	**24,6±6** 24,8±5,5	36,1±15,5 **30,2±24**
$\boldsymbol{M}_z$	**12,6±4,5** 13,9±4,6	29,4±8 **27,4±7,9**	52,8±20,6 **44,3±29,9**

Credit: A. Schuster.

4. Conclusions

This study compares the impact of two cost functions on GRF&M prediction accuracy. The $Pred_{GRF,\tau}$ function, based on minimizing both reaction forces and joint torques, improves lateral force and transverse moment predictions compared to $Pred_{GRF}$ which minimizes only reaction forces and performs better for antero-posterior force. Future work should explore contact-specific weighting to account for the distinct biomechanical roles of hand and foot interactions. Adjusting these weights could improve GRF&M prediction accuracy for in situ motion analysis of military obstacle crossing.

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Conflict of Interest Statement

The authors have no conflicting interests.

Contributor Roles

AS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing original draft; CP: Methodology, Software, Funding acquisition, Validation, Supervision, Writing – review & editing; GD: Methodology, Software, Validation, Supervision, Writing – review & editing.

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Data, software, code availability

The functions and model used in this study are freely available in the CusToM repository.

References

Carlton, S. D., & Orr, R. M. (2014). The impact of occupational load carriage on carrier mobility: A critical review of the literature. *International Journal of Occupational Safety and Ergonomics*, *20*(1), 33-41. https://doi.org/10.1080/10803548.2014.11077025

Graham, R. B., Mir-Orefice, A., Mavor, M. P., Bode, V. G., Doyle, T. L. A., Kelly, K. R., Silverman, A. K., & Sessoms, P. H. (2025). Novel approaches to evaluate characteristics that affect military load carriage. *BMJ Mil Health*, *171*(5), 458–462. https://doi.org/10.1136/military-2024-002899

Muller, A., Pontonnier, C., & Dumont, G. (2020). Motion-based prediction of hands and feet contact efforts during asymmetric handling tasks. *IEEE Transactions on Biomedical Engineering, 67*(2), 344–352. IEEE Transactions on Biomedical Engineering. https://doi.org/10.1109/TBME.2019.2913308

Muller, A., Pontonnier, C., Puchaud, P., & Dumont, G. (2019). CusToM: A Matlab toolbox for musculoskeletal simulation. *Journal of Open Source Software*, *4*(33), 1-3. https://doi.org/10.21105/joss.00927

Skals, S., Jung, M. K., Damsgaard, M., & Andersen, M. S. (2017). Prediction of ground reaction forces and moments during sports-related movements. *Multibody System Dynamics*, *39*(3), 175–195. https://doi.org/10.1007/s11044-016-9537-4