Stiffness and damping of the neuro-musculoskeletal system cannot be estimated adequately using a stiffness-damping-inertia model

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INTRODUCTION
Visco-elastic properties of the (neuro-)musculoskeletal system play an important role in the control of posture and movement. Often, these properties are estimated in vivo using 2nd-order stiffness-damping-inertia (KBI) models. In such an approach, perturbations are applied to the musculoskeletal system and subsequently parameters of the KBI model are optimized to obtain a best fit between simulated and experimentally observed responses. However, in the real musculoskeletal system the skeleton interacts with a visco-elastic contractile element (CE) in series with an elastic tendon (SE); a system of at least 3rd order. This raises three questions: i) can a KBI model adequately describe the behavior of the higher order musculoskeletal system, ii) what information about the underlying musculoskeletal system is captured by the estimated stiffness and damping, and iii) how sensitive are those parameters to measurement errors?

METHODS
A 3rd-order 1DF musculoskeletal model (MSM) actuated by a Hill-type muscle (Fig. 1A), was used to simulate responses to moment perturbations. Subsequently, parameters of the KBI model (Fig. 1B) were determined to reproduce the MSM’s response. Analytical approximations of the optimal fit were derived to investigate the relation between fitted and actual dynamical parameters. A sensitivity analysis was used to assess the range of KBI parameter values that would still yield an adequate fit of the MSM response.

RESULTS and DISCUSSION
The KBI model was not always capable of adequately describing the behavior of the MSM; not even for time windows as small as 100 ms at moderate levels of KCE, BCE and KSE (see Fig. 2), as often suggested in the literature. Simulations and analytical analyses showed that the optimally estimated stiffness and damping depended not only on a non-linear mixture of all dynamic parameters of the MSM, but also on the frequency content of the perturbations applied (see Table 1). Perhaps most problematic, it was found that estimated stiffness and damping were very sensitive to small measurement and/or optimization errors.

These results show that 2nd-order KBI-models do not adequately characterize the behavior of the 3rd-order MSM, and this will be all the more true for the real neuro-musculoskeletal system as it is of even higher order. This suggests that great care should be taken when interpreting and using stiffness and damping values obtained by fitting KBI models.

References