Experimental vs. model-based comparison of stepping threshold in response to external force-controlled perturbation

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Experimental vs. model based determination of stepping threshold in response to external force-controlled perturbation.

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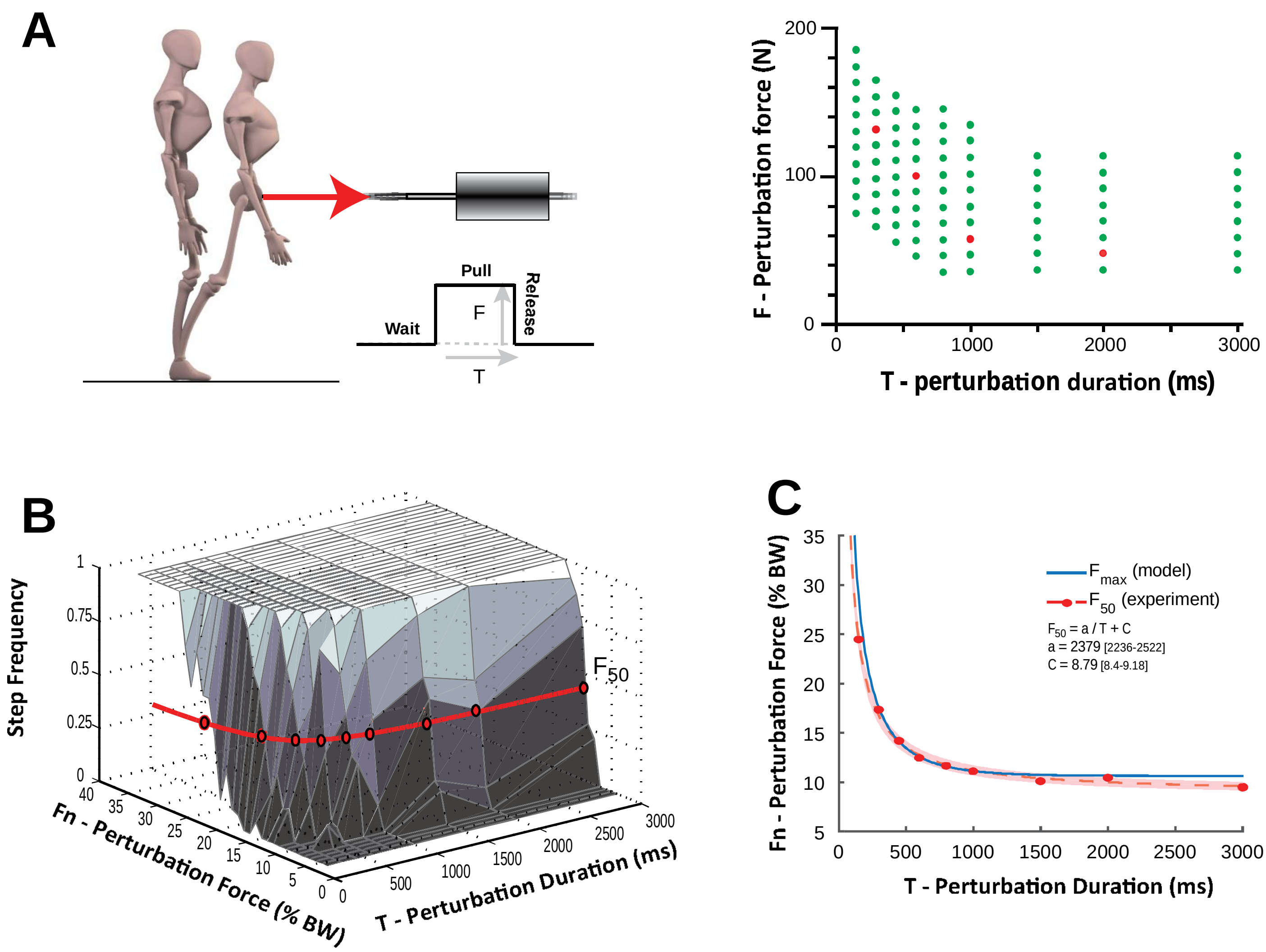
Background and aim. Stepping is a common protective strategy for dynamic balance recovery following external perturbations of stance. The present study investigated the threshold for triggering a step during force-controlled forward perturbations of different durations delivered at waist level, and confronted the experimental results with a simple biomechanical model that could predict when a subject had to step.

Methods. Twenty-two healthy young adults (5 women; 19-37 years old) were asked to try not to step in response to 86 different force/time combinations of forward waist-pulls (Fig A). Each trial perturbation was characterized by its force (Fn - normalized according to the subject body weight), its duration (T), and its consequence (step or no-step). The probability to step as a function of perturbation characteristics was then calculated for the entire group and the force at which 50% of the subjects stepped (F_{50}) were identified for each tested perturbation duration (Fig B). Experimental results were compared to a numerical criterion used to estimate if a recovery step was necessary for a given square force perturbation. It was obtained from the dynamics of a linear inverted pendulum + foot model, considering that the maximal balance recovery reactions. These were an instantaneous shift of the center of pressure at the edge of the functional base of support (CoP*max=15,3 cm*) that arises after the perturbation (delay representing the reaction time RT = 116 ms). Values of CoP_{max} and RT were obtained from the experimental measures.

Results. The experimental stepping boundary was well described by a simple hyperbolic function with a positive horizontal asymptote: $F_{50} = a/T + C$, with *a* the constant defining the radius of curvature of the function and *C* the horizontal asymptote describing the smallest force necessary to trigger a step - any force smaller than *C* could be sustained indefinitely without a step. The results of this fitting (Gauss-Newton, nonlinear, least-mean-squares) is represented on Fig C (red line) and the mean squared error was very small (MSE 0.12). The values of F_{max} computed using the biomechanical model (Fig C solid blue line) correctly predicted the pulling force threshold.

Conclusions. The stepping boundary describes the maximal force that has to be applied for a specific time to trigger a step. Experimentally, this boundary corresponded to a constant impulse (i.e. constant perturbation force and duration product), which could be easily applied in a clinical environment. When compared to the biomechanical model, the stepping boundary was mainly explained by the RT and the CoP displacement within the functional BoS (CoP_{max}). Future work could investigate clinical population to further test validity of both stepping boundary methods and their predictive capabilities.


A
Pull
Wait
F
Release
T
F - Perturbation force (N)
200
100
0
0
1000
2000
3000
T - perturbation duration (ms)
B
Step Frequency
1
0.75
0.5
0.25
0
F50
40
35
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
Fn - Perturbation Force (% BW)
T - Perturbation Duration (ms)
C
Fn - Perturbation Force (% BW)
35
30
25
20
15
10
5
Fmax (model)
F50 (experiment)
F50 = a / T + C
a = 2379 [2236-2522]
C = 8.79 [8.4-9.18]
0
500
1000
1500
2000
2500
3000
T - Perturbation Duration (ms)