

Crouch Gait is More Stable than Normal Gait

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1 Introduction

Normal gait is a pattern of walking that humans normally adopt in undisturbed situations. Gait patterns are considered to be either abnormal or impaired if they do not satisfy certain key attributes of normal gait. It has previously been postulated that normal gait is more energy efficient than abnormal or impaired gait. However, it is not clear whether a normal gait pattern is also superior to abnormal gait patterns with respect to other factors, such as stability.

We studied this issue in two sets of experiments with human participants and a simulated biped using technologies developed in computer graphics. The experiments evaluated the degree of resilience to external pushes for various gait patterns including crouch gait, which is a typical example of abnormal gait and can also be observed in seemingly unrelated situations; e.g., healthy individuals in destabilizing environments, patients with cerebral palsy, and even humanoid robots. We conducted the push experiments with human participants using motion capture technology and with a simulated biped by adopting a state-of-the-art locomotion controller.

2 Experiments with Human Participants

We conducted a series of experiments with thirty healthy participants (15 males/15 females). Participants walked along a straight line with various gaits. An experimenter pushed the shoulder of the participant using a boxing pad to apply a modest, impulsive force. And the participants were asked to return to the straight line after pushing. The participants wore tight suits with retro-reflective markers for optical motion capture. Vicon’s NexusTM software was used to reconstruct three-dimensional marker positions and skeletal motion, and to estimate the Center of Mass (COM) of the skeleton.

To determine their reference walking speed and stride length, participants were first asked to walk with the normal gait that felt most comfortable. Then, they were asked to walk with various speeds, stride lengths. The experimenter included variations in push direction and push timing. For the crouching condition, they walked at a self-selected speed and stride length in varying degrees of crouch ($0^\circ/20^\circ/30^\circ/60^\circ$). Straps were fitted to enforce crouch walking. The measurement data from motion capture include angle of crouched knees, stride length, walking speed, the timing, magnitude and direction of the push, and the angle of the feet at ground contact. We also

measured the height, weight, BMI, and leg lengths from each individual. The maximum lateral displacement of the participant’s COM during three post-perturbation steps was found to be the most reliable measure of how stable the participant was during the disruption. It captures the effect of the initial sidestep, but also how quickly the participant recovers.

3 Simulation Experiments

We wish to determine whether computer simulation using a physically-based biped controller would respond similarly to external pushes. We adopt a data-driven controller [1] for our experiments since it easily generates gait variations by editing a reference gait pattern kinematically. This controller is equipped with full-body tracking capability for imitating reference gaits and feedback rules for maintaining its balance against external pushes.

We randomly selected one motion capture clip as a reference for the normal gait and modified it to generate variations of normal and crouch gaits that we had tested with the human participants. The gait variations $M(\alpha_c, \alpha_l, \alpha_s, \alpha_f, \alpha_t)$ are parameterized with five parameters, where α_c , α_l , α_s , α_f , and α_t are random variables for the level of crouch, stride length, walking speed, the magnitude and timing of push, respectively. α_c is a categorical random variable that chooses a value uniformly from $\{0, 20, 30, 60\}$. Gait parameters are sampled from a multivariate normal distribution. Each gait sample is instantiated from the reference normal gait by using motion displacement mapping and timewarping [2, 3], and fed into the controller for push-recovery tests. The magnitude, direction, and timing of pushes were also drawn from the distributions of the human experiments. A gait sample passes the test if the biped walks with the particular gait and maintains its balance after random pushing at least for 10 seconds.

4 Statistical Analysis

We collected two groups of data. *Group 1* includes 228 cases of human data and 3858 cases of simulation data, in which the lateral displacement peaked within one step. *Group 2* includes 450 cases of human data and 13707 cases of simulation data, in which the lateral displacement peaked within three steps. Having to take three steps to stop deviating further means that they experience difficulties recovering balance. Note that *Group 2* is a super set of *Group 1*.

The linear mixed model (LMM) is a general method for han-

	Test for Fixed effects (F-value and p-value)							
	Level of Crouch		Magnitude of Push		Walking Speed		Timing of Push	
	F_c	p_c	F_t	p_t	F_s	p_s	F_t	p_t
Human Participants ⁽¹⁾	17.49	<.0001	13.42	0.0003	2.68	0.1098	14.35	<.0001
Simulation ⁽¹⁾	30.06	<.0001	175.46	<.0001	106.56	<.0001	463.41	<.0001
Human Participants ⁽²⁾	8.35	<.0001	0.01	0.9297	0.03	0.8578	3.94	0.0479
Simulation ⁽²⁾	88.34	<.0001	191.03	<.0001	371	<.0001	225.79	<.0001

Table 1: Linear mixed models that minimize Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The superscript (1) and (2) indicates Group 1 and Group 2, respectively. Grey cells are statistically significant ($p < 0.05$).

dling the between- and within-subject variability in the repeated, unbalanced data [4]. We use a LMM to model the mean of detouring distances and assess covariate effects. The level of crouch is a categorical variable. The distance values for each crouch level were adjusted using a LMM with fixed effects and each participant as a random effect. Among many potentially influential variables, we need to identify a small number of fixed effects that significantly affect detour distance. To do so, we repeatedly chose a combination of three to five variables to build a LMM and evaluated its competence. The Akaike’s information criterion (AIC) and the Bayesian information criterion (BIC) are common tools for selecting among different competing models to fit a given data set. We found that a LMM with walking speed, push magnitude and timing as fixed effects minimized AIC and BIC (Table 1).

The Bonferroni test confirms that crouch gait is more resilient against external pushes than normal gait (Figure 1). Normal gait was the most vulnerable to external pushes and the stability improves significantly with moderate (20° to 30°) crouching. The lateral detour distance is also related to walking speed and the magnitude of push force and its timing. It detours less if it walks faster, the push is weaker, and the push happens later in the swing phase.

5 Discussion

To summarize the results, our statistical analysis identified significant factors that affect the push-recovery response in biped locomotion: the level of crouch, walking speed, push force and push timing. While the effect of crouching and push force were expected, the influence of speed and push timing were discovered inadvertently in our experiments. Interestingly, height, weight, BMI, stride length, and the direction (left or right) of pushing were irrelevant.

The most cited causes of crouch gait in individuals with cerebral palsy are contraction of muscles and lever arm dysfunction [5], which orthopedic surgeons therefore focus on correcting through muscle lengthening and other procedures. Simply speaking, it has been commonly believed that structural (muscle and bone) deformities cause abnormal, crouch

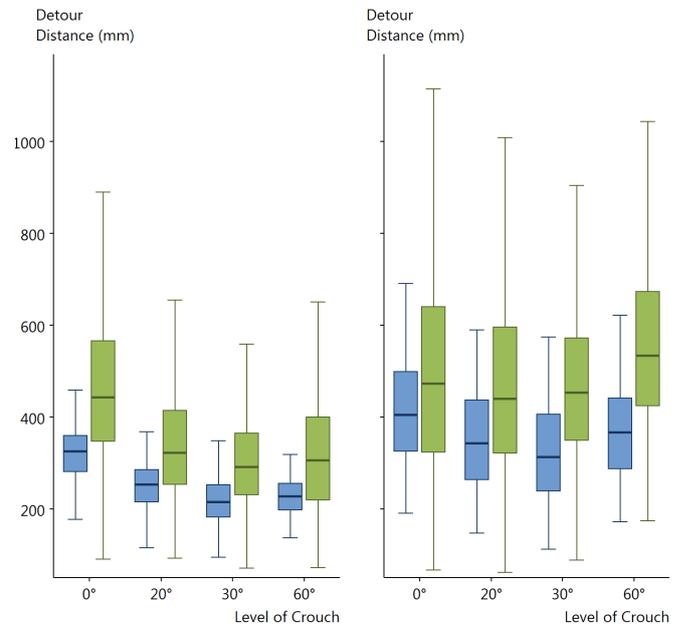


Figure 1: Mean detour distances by crouching for Group 1 (left) and Group 2 (right). Blue boxes represent human data and green boxes represent simulation data.

gaits. Our experiments could provide a new insight into the causality of muscle contracture and flexed knees in patients with cerebral palsy. Such individuals suffer from a lack of muscle coordination, muscle weakness and exaggerated reflexes, and thus have difficulty walking even before the other symptoms become apparent. They might naturally seek strategies to improve stability and balance by crouching, which over an extended period of time might in turn lead to limited range of motion in the knees and other lower limb joints. Our analysis therefore suggests that both crouch gait and structural deformities such as muscle contracture mutually reinforce each other in the developmental process, rather than one causes the other unilaterally.

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