THE DYNAMIC SENSORIMOTOR REGULATION OF FINGERTIP FORCE VECTORS IS INDEPENDENT OF HAND STRENGTH

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INTRODUCTION

We currently lack quantitative and objective measures of sensorimotor ability for dynamic manipulation. Such measures are essential for quantifying hand impairment and comparing treatment outcomes. The dynamical behavior of the brain-hand system during manipulation is extremely complex and nonlinear. Fortunately, bifurcation theory (a branch of nonlinear dynamics) shows that even complex systems behave like low-order systems at the verge of instability (*Guckenheimer et. al, 1983)*. Activities of daily living often involve dynamic regulation of fingertip forces to stabilize objects (e.g., rolling a pen, sliding grasps, etc) (*Valero-Cuevas et. al, 2003*). Thus, we propose that bifurcation analysis can be used to grade sensorimotor ability of the brain-hand system. In this study, we characterize the performance of the brain-hand system at the boundary of instability. We establish that the ability to control or postpone instability is a consistent measure of the sensorimotor ability to dynamically regulate thumbtip force. This motivates the future use of bifurcation analysis to understand sensorimotor function in dynamic manipulation, and clinically grade its impairment.

METHODS

As in our previous work, (*Valero-Cuevas et. al, 2003*), we have developed a task that consists of asking subjects to use their thumbtip to compress a slender spring prone to buckling. We now instrument the spring to measure how the brain-hand system fails to fully compress the spring. We selected a spring that buckled at very low loads with little shortening to maintain a near constant thumb posture, as in key pinch. The calculated buckling loads (*Haringx, 1948*) for the 1st, 2nd and 3rd modes of this spring are (buckling load / shortening): 1.6 N / 2.3mm, 7.0 N / 10mm and 15.2 N / 21.7 mm, respectively.

All subjects read, understood and signed the consent form approved by Cornell's "University Committee on Human Subjects." All 11 participants were unimpaired young adults (age: 29±7 years, 6 females). They placed their dominant hand on a table with the palm perpendicular to the tabletop and positioned their thumb pulp on a flat pad attached to the free end of the vertical slender spring attached to ground. The instructions to the subjects were to "*compress the spring as far as you can, even if the spring oscillates or is not straight, and hold the spring at this shortest length for a few seconds*." The free end of the spring was instrumented with a miniature 3-axis accelerometer to measure $\ddot{\underline{x}}(t)$. The fixed end was attached to ground via a uni-axial load cell to measure the compressive spring force. In five subjects, a 12-camera vision system (Vicon, Inc) tracked the 3D position and orientation of the free end of the spring to measure $\underline{x}(t)$. We also recorded the maximal static pinch strength of all subjects using a pinch meter in key and opposition pinch postures.

RESULTS AND DISCUSSION

Pinch strength varied considerably (mean±coefficient of variance: Key: 87.7 N ± 24%, Opposition: 70.7 N ± 29%), but the variability in maximal compressive spring force was much smaller (23.8 N ± 11%). This suggests that the ability of the brain-hand system to control the buckling instability is consistent across individuals, and independent of their strength.

Moreover, the brain-hand system actively postponed buckling by stabilizing the first 3 modes (cf. mean compressive load vs. spring buckling loads). Stiffening the thumb by co-contraction was likely not the strategy used to reach and hold the boundary of stability, as it is not an effective approach. Co-contraction results in greater fingertip force noise due to increased variability in force production associated with higher muscle recruitment. In contrast, minimizing noise in fingertip force is instrumental to maximizing the shortening of a slender spring past its 3rd buckling mode, as it is in a highly unstable state. Using the lowest possible level of muscle activity is, therefore, a more effective strategy than co-contraction. Although EMG will be collected in future to quantify the degree of co-contraction, it is most likely that subjects had to actively regulate fingertip force to control the unstable spring past its 3rd buckling mode.

Lastly, a clear onset of instability was observed both in position and acceleration data at a critical load (Fig 1). This is strongly indicative of the occurrence of a bifurcation. Future studies will fit low order models (normal forms) to the time-varying

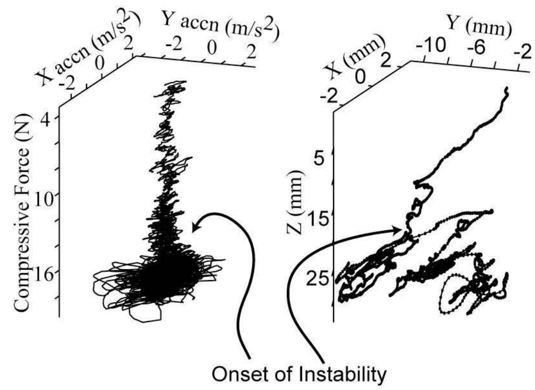

Figure 1: This graph shows representative acceleration (left) and position (right) data as the subject compresses the slender spring and reaches the verge of instability (bifurcation).

data to characterize the exact type of bifurcation that occurs.

We conclude that the maximal compression of the spring is consistent across people of different strengths, and could be used as a measure of the sensorimotor ability to dynamically regulate fingertip force. These results also motivate future work to use normal forms to quantitatively characterize the contribution of passive tissue properties and sensorimotor ability of the brain-hand system during dynamic manipulation in able and impaired hands.

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ACKNOWLEDGEMENTS

Prof. Jessica Hodgins and Jin-Xiang Chai at CMU for use of their motion capture system.