Implicit Accuracy Constraints in Two-Fingered Grasps of Virtual Objects with Haptic Feedback

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ABSTRACT

Using virtual objects that provided haptic feedback we studied two-fingered movements of reaching to grasp and lift an object. These reach-grasp-lift movements were directed to objects of identical physical size but with the different physical properties of mass, and coefficient of friction between the floor and object. For each condition, the resulting forces and kinematic properties of movements were recorded after a brief amount of practice with reaching to grasp and lift the object. It was found that for conditions where the object was more stable to perturbation, such as large mass or high friction, the contact force with the object was greater. This suggests that the stability of the object, is quickly and easily learned and subsequently influences the accuracy of the movement. The possibility is discussed that such programming of contact force is incorporated into the planning of grasps and how this would interact with the execution of grasps to virtual objects with and without haptic feedback

Keywords

grasping, haptic interaction, virtual reality, motor control

INTRODUCTION

Reaching out to grasp and lift an object involves the problem of not only controlling the arm as it moves towards the object but also controlling the arm plus the object after contact. This continuous action of reach-grasp-lift has commonly been examined primarily as two separate problems of 1) reaching to grasp and 2) lifting. Research into these two problems have indicated that expectation and learned models of the arm, hand and environment contribute significantly to the regularities observed in both actions. In the present research, we focus on how learned models of the object to be grasped influence impact with the object in the transition from reach to lift in the continuous motion of reach-grasp-lift. Our examination of the reach-grasp-lift movement was done using a virtual environment including haptic feedback that enabled us to synthesize virtual objects with both visual and haptic properties and study interaction with these objects.

In an earlier study examining grasps to virtual objects that did not provide haptic feedback it was found that, in comparison to grasps with real objects, the grasps to virtual objects had longer deceleration phases and were more variable in their endpoint position [5]. It was conjectured that this difference was mainly due to the lack of impact with an object at the end of the reach to grasp movement, namely that contact with the object is used strategically to assist in braking the motion of the hand. Support for this view comes from studies in pointing movements where it has been found that contact forces are incorporated in the programming of pointing movements [8]. In grasp, although it is generally accepted that preprogrammed grasp movements incorporate aspects of the size and distance to the object [2, 3, 4, 7], there is not abundant evidence that grasping motions are sensitive to the dynamics of the object to be grasped. However, evidence exists that surface texture and other intrinsic properties of an object modulate the reach to grasp motion [1, 6].

In the present experiment we wished to explore whether contact forces were influenced by the properties of the object to be grasped. We examined this by having participants grasp virtual objects simulating different masses and friction relations between the object and floor. By performing 10 practice trials participants became acquainted with the object properties and then data was taken of the reach-grasp-lift motions. It was predicted that contact forces would be learned implicitly, and be related to the accuracy constraints demanded by interaction with each object. Specifically that heavy objects stuck tightly to the floor would be struck with significant force while light objects on a slippery floor would be struck lightly. Positive results would not only suggest a role for the programming of contact forces in the planning of reach to grasp movements, but would also indicate possible advantages of incorporating haptic feedback for interactions with virtual objects.

METHODS

Apparatus

Both the visual stimuli and the force feedback upon contact were programmed within a virtual environment constructed with a graphics computer, head-mounted display and haptic interface device. At the heart of this virtual environment is a graphics generation system run by a Silicon Graphics Onyx processor equipped with four R10000 processors and an Infinite Reality rendering engine. In addition to generating the graphics, the Onyx is equipped with a high-speed serial board capable of simultaneous communication with the head-tracker and haptic interface device. The head mounted display used was a Virtual Research V8 composed of two 1.3 LCD panels which were capable of producing a true 640X480 VGA display. The haptic interface was obtained with two extended-range Phantom haptic feedback devices from SensAble Technologies that allowed the thumb and index finger to be tracked and force feedback applied. The workspace of the combined Phantoms is approximately 400 X 600 X 800mm. The DC motors powering the Phantoms were capable of exerting over 20 N of force to the fingers. The ability of the Phantoms to collect data of position and force at the fingertips varied with the computational load upon the system, and was 400 Hz on average.

Stimuli

The visual stimuli consisted of spheres representing the fingertip positions and a flat sheet which served as the floor upon which the cube to grasp was placed. The dimensions of the cube were 35 X 35 X 50mm, with grasps directed across the 50 mm side. The spheres representing fingertip positions had a radius of 5 mm. The flat sheet had dimensions 300X 400mm and appeared at the level of the table upon which the fingers rested. Taking the origin of this sheet to be at its center, and the close left corner to have coordinates of (-200, 150), the fingers of the right hand started their movements at position (75, -150) and the object was located to have its center at position (-65, 95). In addition there was a small sphere of radius 5 mm placed 130 mm above the center of the cube, which served as a visual signal of the height to which the object should be lifted. All the objects were rendered using lambertian shading and diffuse and point light sources.

The haptical properties were varied to obtain cubes of different weight and different frictional relations with the floor. These manipulations resulted in cubes of different weight that due to friction with the floor were more or less sensitive to displacement forces. The friction between the fingertips and the cube was held constant. For the experiment 3 object weights were used simulating mass (M) of 50, 100 and 200 grams. Four static coefficients of friction (μ_s) were used, simulating values of 0.12, 0.30, 0.65 and 1.0. The dynamic friction coefficients (μ_d) corresponding to these 4 values were 0.12, 0.12, 0.48 and 0.82 respectively. The experiment consisted of a weight series of the 3 weights with the coefficient of friction held constant at 0.65 for static and 0.48 for dynamic, and a friction series of the 4 frictional values with the mass held constant at 68 grams. A summary of these values is presented in Table 1.

condition	M (grams)	μ_s	μ_d	μ_s M
1	50	0.65	0.48	32.50
2	100	0.65	0.48	65.00
3	200	0.65	0.48	130.00
4	68	0.12	0.12	8.16
5	68	0.30	0.12	20.40
6	68	0.65	0.48	44.20
7	68	1.0	0.82	68.00

Table 1. Mass and friction values for the 7 different experimental conditions. The rightmost column of μ_s M provides an estimate of the different relative amounts of force required to move the object.

The visual properties of the object to be grasped were held constant except for the color of the object which was varied to serve as an indicator that the cube to be grasped was the same or different from previous cubes.

Procedure

The experiment consisted of examining reach-grasp-lift motions towards objects in the 7 different simulated conditions (consisting of the weight series of 3 conditions and the friction series of 4 conditions). For an individual trial, a participant began with their thumb and index finger at the start position. At the go signal they reached out to grasp the cube and then lifted it to a height of 13 cm and held it steady before placing it back down on the floor and returned their fingers to the start position. Each trial was self paced and approximately 8 seconds of data were recorded for each trial.

The 7 different conditions were blocked so that participants could become accustomed to each experimental condition. For each block a participant performed 20 lifts, of which the first ten served as practice and the last ten were recorded for subsequent data analysis.

Data was recorded from 3 participants, all of whom were naive to the purpose of the experiment. The entire experiment took approximately 45 minutes.

RESULTS

Data from individual reach-grasp-lift records were analyzed using software written in Matlab. This processing of data included a preliminary step of preprocessing, followed by extraction of relevant forces and kinematic markers to characterize the movements. The preprocessing involved first using linear interpolation to have each record evenly sampled at a rate of 500 Hz. Following this, the interpolated data were filtered with a 2nd order dual pass butterworth filter with a lowpass cutoff of 8 Hz. First and second derivatives of the position and force data were obtained through the use of central difference equations.

Estimates of the startpoint of the movements were found by averaging together the velocity of the two fingers and finding the first 3 points which had greater tangential velocity than 5% of the maximum velocity. Estimates of the endpoint of the movements were taken from the time that the first finger hit the object. The time of impact was taken as the time of the first peak of the first derivative of force for either finger. Examination of the first derivative of force was limited to between time of maximum aperture and time of maximum vertical position of the lifted object.

Kinematics

Reach to grasp movements are typically thought of as involving the relatively independent components of transport and preshape [2]. The maximum velocity, acceleration and deceleration of the wrist characterize the transport component, and the maximum aperture between the two fingers characterizes the preshape component. Since in the current study there were no measurements of the motion of the wrist we used the average velocity of the two fingers to estimate properties of the transport component. The magnitudes of these kinematic markers are shown in Figure 1 and their temporal sequencing of is shown in Figure 2 where time has been normalized so that time=1 is equivalent to the first touch of the object. Visual inspection of Figures 1 and 2 indicate slight deviations between the weight series and the friction series as well as within each series.

Closer examination of the results was obtained by performing, for each combination of participant and kinematic marker, a one factor repeated measures ANOVA which examined the effect of object condition on the kinematic marker. Result of these analyses showed that at a $p<0.05$ level of significance, condition had an effect on maximum velocity for all three participants, maximum aperture for two participants, maximum acceleration for one participant and maximum deceleration for none of the participants. Further statistical analysis was performed on the average data of all three participants and it was found that there were statistically significant effects of condition for these kinematic markers which that involved higher order interactions with participants. However, possibly due to the small number of participants, these individual differences appeared to fall into no regular pattern.

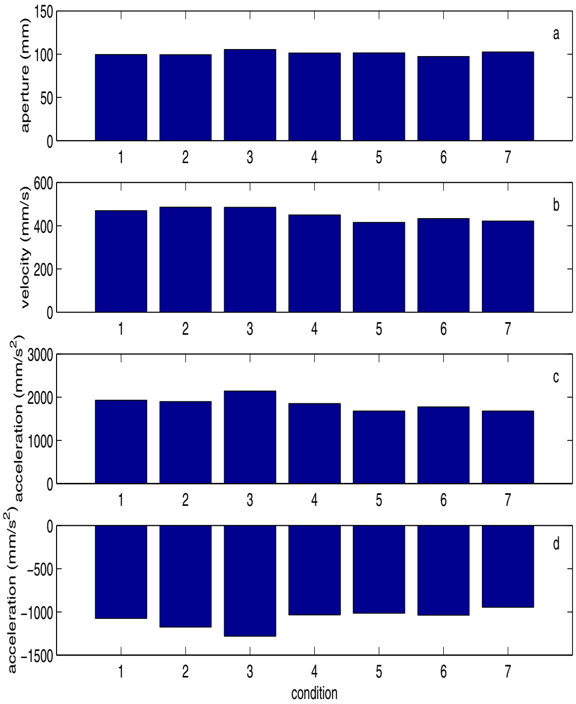

Figure 1. Values of the a) maximum aperture, b) maximum velocity, c) maximum acceleration and d) maximum deceleration for the 7 different experimental conditions.

Contact Forces

Of primary interest for the current research was an estimate of the contact force with the object. Estimation of a contact force is problematic in the sense that there are two fingers involved in hitting the object and contact of the two is possibly simultaneous. Our definition of contact force was taken to be the maximum difference between the two finger forces that occurred in the first 100ms after contact of the first finger on the object. For this measure we only considered forces in the horizontal plane, ignoring the vertical component of force. We restricted our analysis to these horizontal forces since our primary interest was in forces which would displace the object and thus make it more difficult to initiate a lifting motion. An example of this measure is shown in Figure 3. The rationale for this choice was that the 100ms time window should be short enough to avoid sensory feedback while still long enough to indicate whether the object was being met simultaneously with near equal forces or nonsimultaneously with a large collision force by one of the fingers.

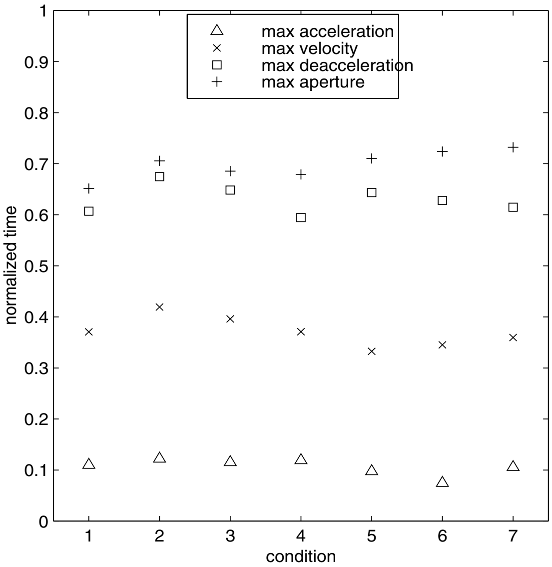

Figure 2. Temporal sequencing of the kinematic parameters for the 7 different experimental conditions. Time is normalized so that first contact with the object corresponds to the time of 1.

Our hypothesis was that the various simulated conditions would provide different accuracy constraints for grasping and lifting the object. In other words, we would expect that the measured contact forces should be proportional to the threshold force with which the object could be struck before it moved. An examination of this hypothesis is shown in Figure 4 where we have plotted the measured contact force versus μ_s M. It can be seen that the relationship between these two factors is consistent with the hypothesis that objects that can withstand a greater contact force before moving will receive a greater contact force.

Finally, we wished to examine the previously mentioned kinematic markers to see if the kinematic values obtained could have been related to the contact force. Figure 5 shows the maximum aperture, maximum acceleration, maximum velocity and maximum deceleration versus the contact force for each of the 7 conditions. As can be seen there was a general trend for the maximum aperture to increase with increasing contact force. Similarly, as for increasing contact force there was a tendency for the movement to accelerate quicker, reach a higher maximum velocity and then decelerate quicker.

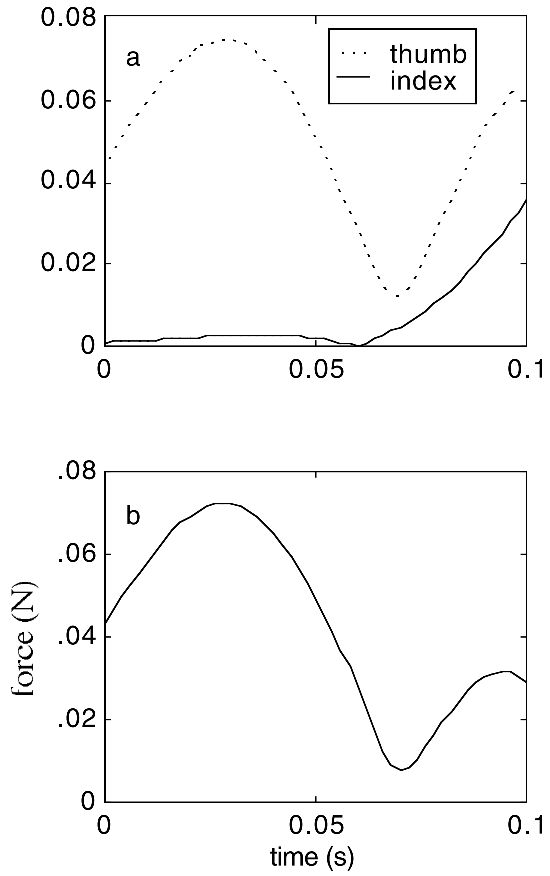

Figure 3. Example of the calculation of contact force. In (a) we see the timecourse of force measurements for both the thumb and the index finger. In (b) we see the difference between these two curves. The corresponding estimate of the contact force would be approximately 0.07 Newtons as found on the peak of the curve shown in (b). For both (a) and (b) time of zero corresponds to contact of the first finger with the object.

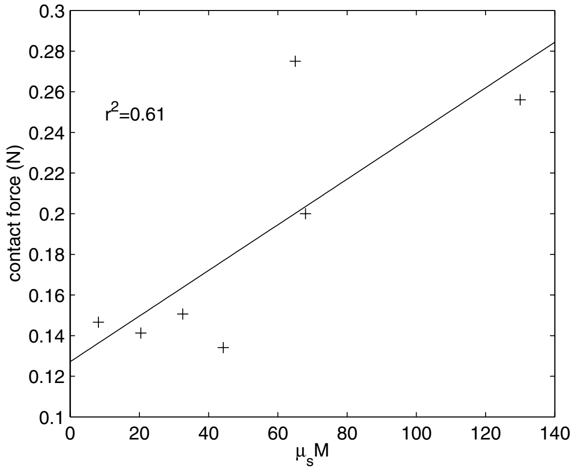

Figure 4. A plot of the measured contact force versus the quantity μ_S M for each of the 7 experimental conditions. A linear regression was performed on the points and the resulting line is shown on the graph as well as, r^2, the percentage of variance accounted for by the linear relationship. The predicted relation is that contact force should increase for experimental conditions with higher values of μ_S M.

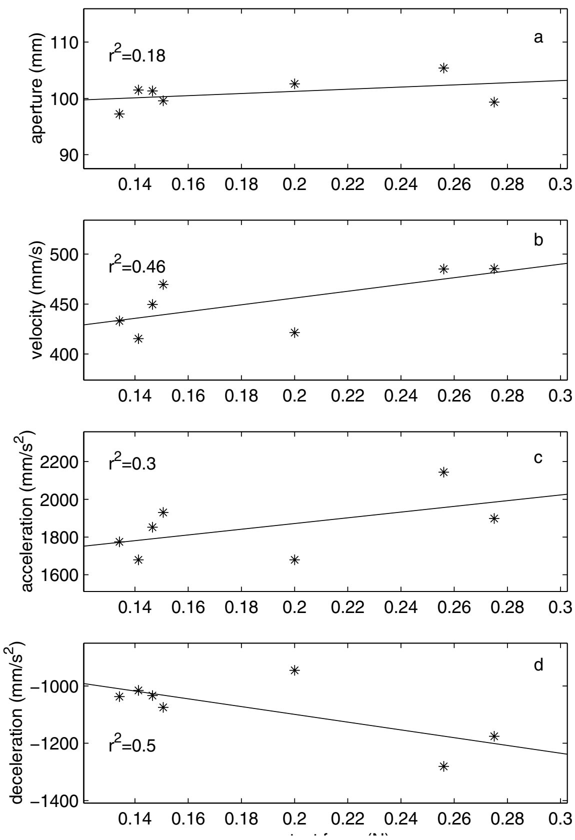

Figure 5. The four different kinematic markers of a) maximum aperture, b) maximum velocity, c) maximum acceleration and d) maximum deceleration are plotted versus the measured contact forces. Each graph includes the resulting linear regression line and the corresponding value of r^2.

DISCUSSION

The results were consistent with the hypothesis that contact forces would increase as the virtual object was more stable and thus capable of absorbing greater force before moving. In addition to these differences in contact forces it was found that the standard kinematic parameters used to describe grasp were found to covary with the contact force. The grasps to these more stable objects had apparently larger apertures and greater velocities - kinematic values which are characteristic of low accuracy grasps [9]. It thus appears that the programming of contact force with an object is intrinsically involved in the planning of grasp accuracy.

The results suggest that incorporating haptic interaction with objects would be useful for obtaining natural interactions with virtual objects. Without haptic feedback we can conjecture that the grasp kinematics would tend towards the values required when nearly zero contact force must be applied to the object. Thus, for high precision grasps there might be little effect of haptic feedback in modulating the kinematics of grasp. However, for grasps to stable objects we would expect that haptic feedback is key in providing deceleration forces to the hand. Thus, with no haptic feedback grasps to stable objects would likely appear unrealistic.

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