KINEMATICS OF REACHING AND GRASPING WITH A TOOL

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Kinematics of reaching and grasping are observed for prehension performed by the hand (natural prehension) and with a simple grasper held in the hand (remote prehension). Remote prehension is executed with a longer movement time, lower movement speed, extended deceleration phase and a relatively larger peak aperture compared to natural prehension. The kinematic changes in remote prehension are more pronounced when adults reached and grasped an object placed on a narrow than a wide base. Results suggested that the indirect and incomplete proprioception and sensorimotor integration with tool use are the main problems for movement control in remote manipulation. Implications of this study are discussed for design of tools and a safe work environment for tool use.

INTRODUCTION

Tool use is a fundamental activity of human kind. However, we have little understanding of the processes underlying tool use by human beings. When a tool is added to the motor system, it will cause humans to develop a new mode of movement coordination. The study uses prehension as a standard movement to examine the coordination built between the hand and the tool.

Prehension is a common movement that includes two components - reaching and grasping. Each responds separately to different object properties and they are coordinated with each other in many aspects (Jeannerod, 1981, 1984). Jeannerod proposed a central mechanism for controlling the timing of these two components (Jeannerod, 1981, 1984). However, Wing argued the coordination is built on a spatial aspect (Wing, Turton, & Fraser, 1986). Lately, scientists notice the association between reaching and grasping is not fixed but subject to changes of task requirement (Jeannerod, 1988; Marteniuk, Leavitt, & MacKenzie, 1990).

This study investigates the kinematics of reaching and grasping in prehension performed by the hand and by holding a grasper in hand. For simplification, we use “*natural”* and “*remote”* to name prehension performed by the hand directly or by holding a grasper in the hand. At least two aspects need to be taken into the consideration when controlling a tool – the mechanical properties and the perception difficulties caused by the tool use.

When holding a grasper, the hinge location that alters the aperture ratio may have a significant impact on the aperture profile of grasping. The length of the grasper may modify the velocity profile for reaching. Tool use also adds difficulty for sensory perception of a movement. Lack of direct proprioceptive information is a major problem. It is true that vision will take a role for information searching and compensate the loss of proprioception in the case of tool use (Driver & Spence, 2000; Maravita, Spence, & Driver, 2003; Maravita, Spence, Kennett, & Driver, 2002). However, the ability for visual compensation is moderate. The movement accuracy deteriorates significantly due to the deprivation of proprioception on the movement segments (Rothwell *et al.*, 1982; Taub, 1976). In cases of performing a task requiring a high level of precision with a tool, the impact of insufficient proprioception on task performance may be evident.

In this study, the accuracy requirement was introduced by changing the diameter of the base which supports the object. We predicted that reaching and grasping an object placed on a narrow base would lengthen the movement time and deceleration phase compared to the object on the wide base; the difference between the wide and narrow bases would be more pronounced in remote than natural prehension.

The grasper used in this study had a pivot in the middle of the tool (length ratio = 1), which minimized the impact of mechanical properties of the tool on task performance. We predicted that subjects would open the hand wider in remote prehension due to the limited proprioceptive feedback from the tool compared to natural prehension.

Tasks were required to be performed by the preferred and the non-preferred hand of the subjects. The independent variable of performing was primarily set for an interrelated study on the degrees-of-freedom control of tool use. In this study, the lateralization on manual movement provides us with an opportunity to examine the impact of motor skills on prehensile performance. Movement skills are believed to be more developed on the side of the preferred than the non-preferred hand (Elliott, Roy, & Goodman, 1993).

METHODS

Twelve university students who were naive to the purpose of the study participated in the study. Ethical approval was obtained from Simon Fraser University.

The task was to reach, grasp, and lift up a dowel from either a wide (5 cm) or a narrow (1 cm) base using the preferred and non-preferred hand with and without holding a simple grasper. The graspers used in the experiment were modified from common kitchen tongs. The handle and the object-contact ends of the tongs were cut off; the tongs became a simple device with two straight metal pieces (0.5 cm in diameter) linked by a hinge in the middle. The total length of the grasper was 12.5 cm. When used, the grasper was attached to the pad of the thumb and the index finger by surgical tape. The contact length between the grasper and hand was about 1cm, held constant over all subjects (Figure 1).

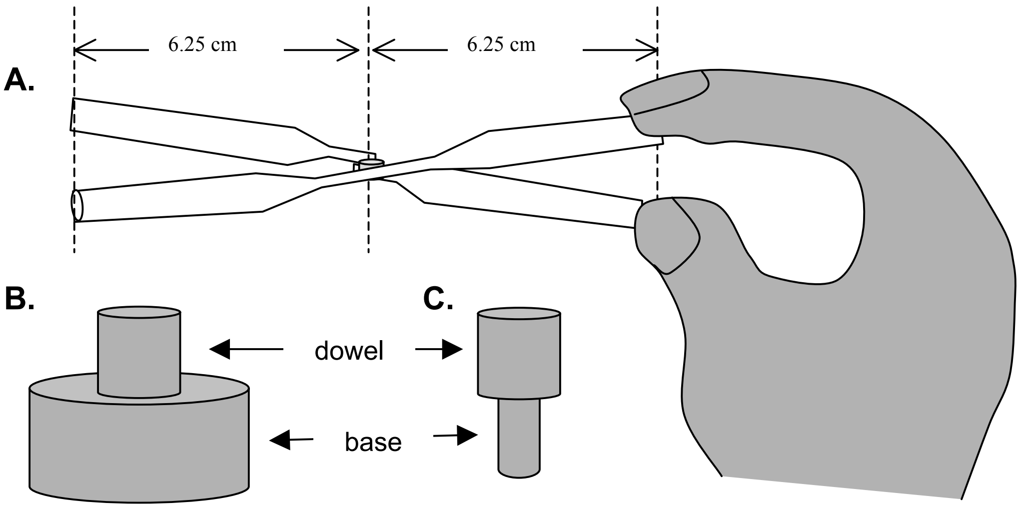

Figure 1. The grasper (A) and the object used for the study. A dowel is placed on a wide (B) or a narrow base (C)

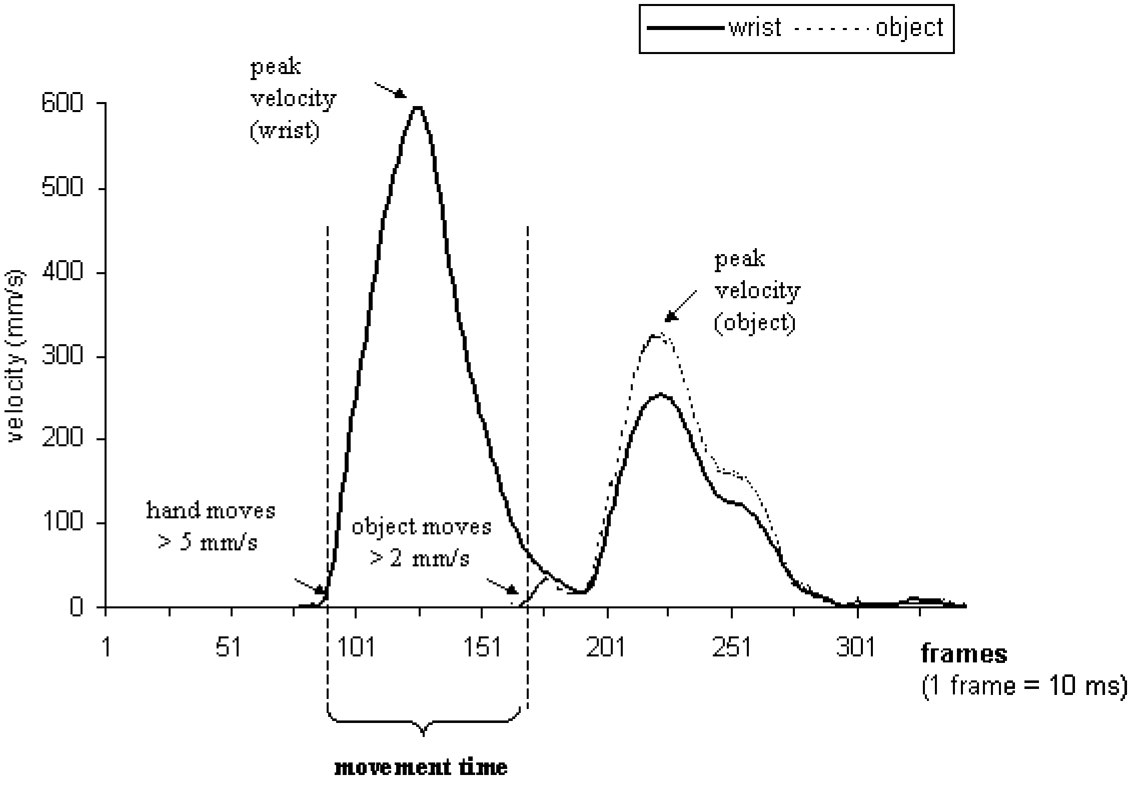

Figure 2. Tangential velocity profiles of the wrist and the object movements. The first occurrence of non-repeating wrist velocity larger than 5 mm/s was defined as the start of the movement; the first occurrence of object movement speed larger than 2mm/s was defined as the end of prehensile movement.

Table 1 Summary of means and standard errors over experimental conditions in natural and remote prehension.

Task		Natural Prehension				Remote Prehension			
Hand		preferred		nonpreferred		preferred		nonpreferred	
Object Base		wide	narrow	wide	narrow	wide	narrow	wide	narrow
MT (ms)	mean	735	746	811	838	908	926	948	1044
	std. error	39	44	34	45	59	48	34	37
PV (mm/s)	mean	644	639	607	601	538	528	540	506
	std. error	23	27	20	26	21	14	24	16
TPV (ms)	mean	363	369	364	379	430	420	408	424
	std. error	12	13	11	16	24	15	14	12
TAPV (ms)	mean	372	377	447	459	478	506	540	620
	std. error	33	37	30	35	38	38	28	31
%TAPV	mean	49	49	54	54	52	54	56	59
	std. error	2	2	2	2	1	2	1	1
PAc (mm/s/s)	mean	3561	3461	3334	3274	2443	2423	2759	2242
	std. error	275	297	270	329	195	143	390	117
TPAc (ms)	mean	200	203	192	205	220	224	212	213
	std. error	10	8	8	12	14	10	10	8
%TPAc	mean	28	28	24	25	25	25	23	21
	std. error	2	2	1	2	1	1	1	1
PDc (mm/s/s)	mean	-2348	-2291	-2011	-1978	-1776	-1677	-2203	-1571
	std. error	190	202	142	162	136	97	578	95
TPDc (ms)	mean	504	520	524	538	598	589	584	608
	std. error	20	22	18	25	32	24	22	19
%TPDC	mean	70	72	66	66	67	65	62	59
	std. error	3	3	2	2	2	2	2	2
PA (mm)	mean	46	52	52	54	57	57	54	57
	std. error	2	2	3	2	2	2	1	2
TPA (ms)	mean	635	635	647	651	722	758	746	806
	std. error	32	34	28	33	42	31	35	41
%TPA	mean	87	86	81	79	81	83	80	78
	std. error	2	2	2	3	3	3	3	3
IID	mean	24	25	27	27	24	24	24	24
	std. error	2	2	2	2	1	1	1	1
adjPA	mean	22	27	25	27	33	33	30	33
	std. error	2	2	3	2	2	2	1	1

Abbreviation: MT, movement time; PV, peak velocity; TPV, time to peak velocity; %TAPV, percent time after peak velocity; PAc, peak acceleration ; TPAc, time to peak acceleration; %TPAc, percent time to peak acceleration; PDc, peak deceleration; TPDc, time to peak deceleration %TPAc, percent time to peak deceleration; PA, peak aperture; TPA, time to peak aperture; %TPA, percent time to peak aperture; IID, initial IREDs difference; adjPA, adjusted peak aperture

Movements were tracked with the OPTOTRAK 3020 system. The position data taken by infrared emitting diodes (IREDs) placed on the wrist, thumb and index finger were used. Data were sampled at 100 Hz, interpolated at 4 frames, and filtered at 4 Hz using the WATSMART program. Figure 2 illustrates the definition of the movement time (MT). MT and other kinematic landmarks were computed, including peak velocity (PV), time to peak velocity (TPV), peak acceleration (PAc), time to PAc (TPAc), peak deceleration (PDc), time to PDc (TPDc), peak aperture (PA), time to peak aperture(TPA). Dependent variables were analysed by a 2 (task) x 2 (hand) x 2 (base) within subject ANOVA using SPSS 11.0.

RESULTS

Remote prehension had a longer movement time (956 ms) compared to natural prehension (783 ms, $P < 0.001$). Reaching and grasping the object on the wide base (888 ms) took longer time compared to the narrow base (851 ms; $P = 0.004$). The preferred hand (829 ms) moved faster than the non-preferred hand (910 ms, $P = 0.003$). In natural prehension, the base width did not show a major impact on the movement (wide 773 ms, narrow 792 ms); however, in remote prehension the effects of base width were amplified (wide 928 ms, narrow 985 ms; $P = 0.017$).

The longer movement time of remote prehension was accompanied by a low movement speed. Peak velocity in remote prehension (528 mm/s) was significant lower than in natural prehension (623 mm/s, $P < 0.001$). Reaching and grasping an object on the narrow base resulted in lower movement speed (569 mm/s) compared to the wide base (582 mm/s, $P = 0.028$). Action by the preferred hand (587 mm/s) achieved a higher movement speed than the nonpreferred hand (563 mm/s, $p = 0.003$).

In natural prehension, maximum movement speeds were achieved earlier (TPV = 369 ms) than remote prehension (TPV = 421 ms, $P = 0.002$). Reaching for an object on the narrow base yielded a longer deceleration phase (TAPV = 491 ms, %TAPV = 54 %) than a wide-base object (459 ms, 53 %). In natural prehension, the deceleration phase was not significantly influenced by the base width (TAPV of wide base 409 ms, narrow 418 ms). However, holding a grasper in the hand significantly extended the deceleration phase when reaching for an object on the narrow base (TAPV = 563 ms) compared to the wide base (TAPV = 509 ms). In other words, holding a grasper in hand amplified the effect of task precision requirements on movement performance.

The aperture analysis revealed a larger PA in remote (56 mm) than natural prehension (51 mm; $P = 0.016$). One might argue that the larger PA in the remote task was due to the relatively larger initial aperture of the hand when the tool was attached to the thumb and index finger. The initial aperture was then computed prior to movement start and was subtracted from aperture profiles. The adjusted peak aperture (adjPA) measures the actual increments of the aperture during the movements.

Again, a larger adjPA was observed in remote (32 mm) than natural prehension (25 mm; $P = 0.002$). The adjPA was affected significantly by the base width (narrow base = 30 mm, wide base = 28 mm, $P = 0.006$). A larger proportion of time was used to reach the peak aperture in natural (83 %) than remote prehension (80 %; $F_{1,11} = 7.37$, $p = 0.020$). In other words, a larger percentage of time was used for closing the hand in remote prehension compared to natural prehension.

The cross-correlation between the measure of time to peak deceleration and the time to peak aperture was computed. Suggested by Jeannerod, these two were the key variables for measuring the temporal coupling of reaching and grasping of a prehension(Jeannerod, 1981, 1984). Correlations between the TPDc and TPA were diverse, only 35 of the 96 (36.5%) correlations were significant. No noteworthy pattern could be found when examining the distribution of these correlations over experimental conditions.

DISCUSSION

Clear kinematic features of remote prehension included longer movement time, lower movement speed, longer deceleration phase and relatively larger peak aperture compared to the natural prehension. We believe the kinematic changes in remote prehension are caused by difficulties in sensory perception and the sensorimotor integration of the movement.

In remote prehension, proprioception is indirect or incomplete, and vision becomes the primary source for perceiving information of the tool. As a result, visual coding and decoding is more complicated in remote than natural manipulation. In the case of performing a difficult task (higher precision requirement), the volume of information transported along a single visuomotor pathway may increase extensively and reach the maximal capacity. The decrease of movement speed and prolonged movement time allows more time to process information. The velocity profile in the case of escalating requirement for sensorimotor mapping will display a unique skew, i.e. significantly longer movement time during the deceleration phase. For example, Marteniuk & MacKenzie identified a longer deceleration phase on the course of reaching and grasping a more fragile object (light bulk) compared to a tennis ball (Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). In this study, deceleration phase for remote prehension was 536 ms, 122 ms longer than natural prehension (414 ms), reflecting the degree of perception difficulty in remote prehension.

Difficulty in obtaining sensory feedback also affects the grasping component. Subjects tended to open their hand wider in remote prehension to prevent from missing the object. In the mean time, subjects reduced movement speed and allowed more time to close the grasper prior to the contact of the object.

A lower correlation coefficient between TPDc and TPA and no noteworthy correlation pattern for natural and remote prehension rejects the notion of temporal coupling between the transport and grasp component. It would be more logical to describe the coordination as a central blueprint that regulates the *functional* output of each sub-movement to ensure the task goal be accomplished, rather than set rigid couplings on a temporal or spatial aspect (Marteniuk et al., 1990).

This study has implications for design of tools and a safe work environment for tool use. In research and development of remote manipulation tools, these kinematic measures like peak velocity, time in deceleration, and peak aperture may be indicators of tool effectiveness for a given task. Further, as we pointed out earlier, the vision becomes extremely important for perceiving information of the tool. A safe work place should provide sufficient illumination when a worker's tasks are performed with tools. In addition, performing with a tool requires extra effort from human users to process information, which suggests a longer time will be allowed for task with tools.

The grasper used in the study was attached to the fingers by tape. This unusual way of holding the tool may limit the generalizability of our findings. Also, the aperture profile that described the movement of the grasp component was measured from the fingertips. Future study on remote manipulation will allow subjects to grip and grasp in a more comfortable way, and grasping outcomes would be detected from both the hands and the tips of these types of graspers.

ACKNOWLEDGEMENTS:

This research was supported by doctoral fellowships to B. Zheng from Simon Fraser University and Michael Smith Foundation for Health Research, and by research grants to C. L. MacKenzie by the Natural Sciences and Engineering Research Council of Canada.

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