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TECHNICAL PAPER

Dynamic phenomena in a ball handling process using a stick

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Abstract Sticks are one of the oldest tools that human beings have used since ancient times. To clarify the characteristics of sticks as tools, we evaluated the impacts of the length of a stick on the number of rolls when a subject rolled a table tennis ball mounted on the axis of a device by using a stick. While the ball turned round 44.5 ± 18.8 times when rolled directly with a finger, the number of its rolls became smaller as the length of the stick became longer; thus, it was 9.9 ± 6.3 with a stick length of 90 cm when it was rolled with a stick. The number of rolls was found to increase with the force applied to the ball and with the maximum velocity of the stick, and was also affected by a deviation angle α_{xz} of the resultant force applied to the ball. From these results, it was clarified that the reason why it became difficult to roll a ball when the length of a stick increased was not only that the force applied to the stick was dispersed but also that the direction of the force was difficult to control.

1 Introduction

A tool is an external object used as an extension of the human body to achieve a certain goal, and tools are deeply connected to the development of human intelligence and culture (Beck 1980). It has previously been shown that the ability of monkeys to procure an object placed at a distance from them was dramatically elevated by using a tool (Maravita et al. 2004). In addition, Hayashi et al. have suggested the possibility that the cognitive ability of primates to survive in the natural world is reflected in the operation of tools (Hayashi et al. 2003).

Among all the human tools, sticks are one of the tools that have been used most frequently since ancient times. Because many chimpanzees dig holes and catch insects such as ants using sticks, it is presumed that the stick is deeply associated with the evolution of human beings as an indispensable tool for hunting, collecting, and so on (Sugiyama 1985). The length of a stick has a great influence on the behaviour and perception of humans and their ability to achieve tasks. There is a linear relation between the perceived length of a stick and its actual length, but a longer stick is felt to be shorter than its actual length (Turvey 1996). The length of a stick bodily perceived by a test subject is affected by its density and mass distribution, and a thicker stick is felt to be shorter (Chan 1995). In addition, when determining length of a stick by gripping it in a condition where the vision is blocked, the range of perception and the result of determining its length vary with its mass distribution (Burton et al. 1991). Bongers et al. (2004) performed an experiment to move an object using sticks that differed from each other in length, mass and mass distribution. They found that when people use short sticks, they stretch their arm bending forward, and by contrast, when they use long sticks, they straiten their posture and bend their elbows close to their bodies. Steen et al. have demonstrated that, when taking a pointing exercise with a stick 10–30 cm long, the articular angle depends on the length of the stick used (van der Steen et al. 2011).

In this study, a ball rolling test was conducted, wherein a ball mounted on a device was rolled at the tip of a stick to elucidate the effect that the length of the stick has on the ability of humans to achieve a certain task and its

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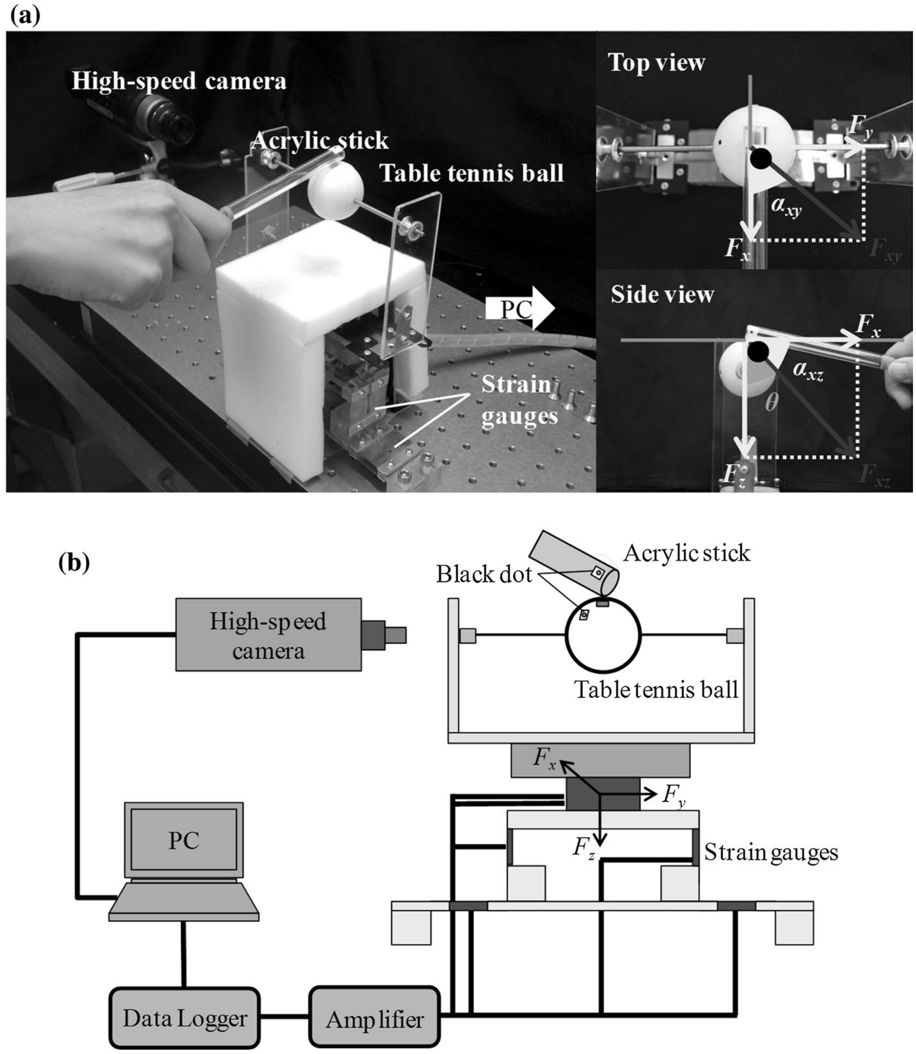

Fig. 1 A ball rolling device. A photograph (**a**) and a schematic (**b**)

governing factor (Fig. 1). The two reasons why a test subject was charged with the task of 'rolling a ball with a stick' are as follows: the first is the fact that the task of moving or pointing at an object with a stick is very easy to generate a variation with its length, whereas a certain technique is required for rolling a ball with a stick and thus has moderate difficulty. The second is the fact that controlling a ball with the tip of a stick is the operation performed not only in sports such as tennis, table tennis and golf but also on touch panel displays, and thus, it is expected to be applied to various fields. In this ball rolling test, a test subject rolled a ball mounted on an evaluation device with the forefinger of her/his dominant hand or using various lengths of acrylic sticks to evaluate the number of rolls based on the high-speed images taken at the time. In addition, the governing factor for the number of rolls was analysed not only by measuring the force applied to the ball using a dynamics sensing system installed in the lower portion of the device but also by observing its movement.

2 Experimental

2.1 Evaluation of the ball rolling ability

The evaluation of the ball rolling ability of test subjects was performed according to the Helsinki Declaration. The performance of this test was authorized by the Yamagata University Ethics Committee, verifying in advance that the test was safe to the body of test subjects and caused little mental stress. The contents of the experiment were explained to the test subjects verbally and with a document for their decision on whether they would participate in the test. Written informed consent was obtained from all participants prior to the experiments. The ball rolling abilities of 30 test subjects, comprising women with ages ranging from 18 to 25, were evaluated using an original ball rolling device located in a quiet room at a temperature of 298 ± 2 K and with a relative humidity of 50 ± 3 %. After wearing a white garment and cleaning both hands with a commercial bubble-type hand soap, each test subject rolled a ball mounted on the ball rolling device using hollow acrylic sticks with lengths of 5, 10, 50 or 90 cm, external diameter of 10 mm and internal diameter of 7 mm (Sugawara Kougei Co. Ltd., Tokyo, Japan) and the forefinger of her dominant hand. The length of the stick was defined as the portion of the stick excluding a 10 cm end section designated for being held in the hand. These evaluation tests were achieved twice with each stick. To reduce the influence of the order in which tools were used on the results, the test subjects were directed to use sticks of different lengths in a random order.

A table tennis ball accredited by the Japan Table Tennis Association (Yamato Takkyu Co. Ltd., Osaka, Japan) was mounted in the midst of the ball rolling device (Fig. 1). A stainless steel stick, SM995-3 (Hikari Seisakusyo, Co. Ltd., Yamaguchi, Japan), penetrated the centre of the ball and was connected to acrylic plates via rollers (Double Aluminium Rollers, w/Rubber Rings, Tamiya Corporation, Shizuoka, Japan). In addition, a normal force F_z in the z direction and tangential forces F_x and F_y in the x and y directions applied to the ball could be measured using strain gauges, KFG-03-120-C1-16L1M2R (Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan), which were affixed to a flat spring at the lower part of the sample table. These strain gauges were connected to PC VW2000 (Keyence Corporation, Tokyo, Japan) for data processing through data logger units NR-500 and NR-ST04 (Keyence Corporation, Tokyo, Japan). The ranges of linear responses of the tangential forces in the x and y directions and of the normal force in the z direction were 0.01–9.67 N, 0.04–7.92 N and 0.05–9.77 N, respectively, and their detection limit was 0.0014 N, 0.013 N and 0.015 N, respectively. These dynamics data were obtained in a cycle of 500 Hz. A high-speed camera VW-9000 (Keyence Corporation, Tokyo, Japan) was connected directly to a data processing PC. The high-speed images were taken at a frame rate of 500 fps. Seals with black dots having a diameter of 2 mm were affixed to three parts: the left-side tip of the forefinger of the test subject's dominant hand, the left side of the acrylic stick and the ball; the finger, stick and ball were irradiated by the lamp unit OP84310 (lamp: metal halide halogen 80 W; color temperature: 6400 K). The velocity of the finger, stick and ball were analyzed using the motion analysis software for VW-9000.

2.2 Analysis of dynamic data and image data

To elucidate the relationship between the direction in which the force was applied and the number of rolls of the ball, a deviation angle of the resultant force F at the contact point of the stick and ball when the normal force was maximum was evaluated (Fig. 1). Resultant forces F_{xy} and F_{xz}, deviation angle α_{xy}, and angle θ were obtained using the following formulae. In addition, a deviation angle α_{xz} was calculated from the high-speed images and the angle θ.

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

$$F_{xy} = \sqrt{F_x^2 + F_y^2} \quad (2)$$

$$F_{xz} = \sqrt{F_x^2 + F_z^2} \quad (3)$$

$$\alpha_{xy} = \tan^{-1}\left(\frac{F_y}{F_x}\right) \quad (4)$$

$$\theta = \tan^{-1}\left(\frac{F_x}{F_z}\right) \quad (5)$$

2.3 Statistical analysis

Effects of the length of the stick on the number of rolls, F, F_x, F_y, F_z, the maximum velocity of the stick v_s, the maximum velocity of the ball v_b, α_{xy} and α_{xz} were analysed. First, the regression equation, $y = a + bx$, was obtained by analysing the data of 30 subjects using the least-square method, where the variable x is the length of a stick, the variable y is the 9 factors described above and a and b are constants. Test conditions were set as the null hypothesis $b = 0$, the alternative hypothesis $b \neq 0$, the reference value $b_0 = 0$ and the data group number $n = 60$. For α_{xz}, however, $n = 58$ was taken because the data acquisition failed twice among 300 trials. The test statistic is $T = \frac{\bar{b}-b_0}{\frac{s}{\sqrt{n}}}$ where $\bar{b}$ and s are the mean and standard deviation of all the test subjects, the degree of freedom = 59 (α_{xz} has the degree of freedom = 57) and the significance probability = 5 %. SPSS Ver. 16.0 was used for these analyses.

3 Results

To clarify the effects of the length of a stick on the number of rolls of the ball, a comparison was made between this number and the length when it was rolled with a finger and a stick 5–90 cm long (Fig. 2). As the length of the stick increased, the number of rolls decreased. For example, the number of rolls was 44.5 ± 18.8 when the ball was rolled using just a finger and was 9.9 ± 6.3 when the length of the stick was 90 cm, where the figures before and after the '±' symbol are the mean and standard deviation, respectively. The test statistics T of the parameter b value that was obtained when the relationship between the number of rolls and the length of the stick was analyzed using the

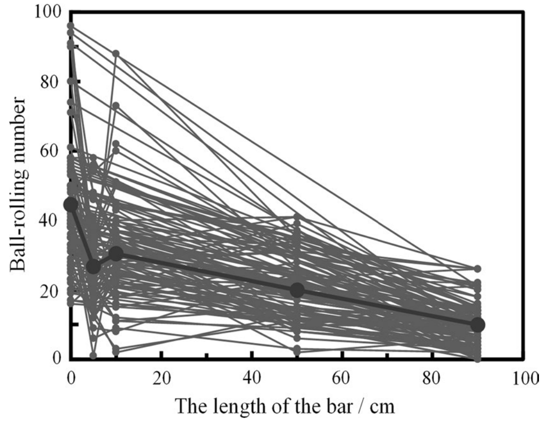

Fig. 2 The relationship between the length of the stick and the number of rolls of the ball: *filled circle* the mean of 30 test subjects, *filled circle* data for each test subject

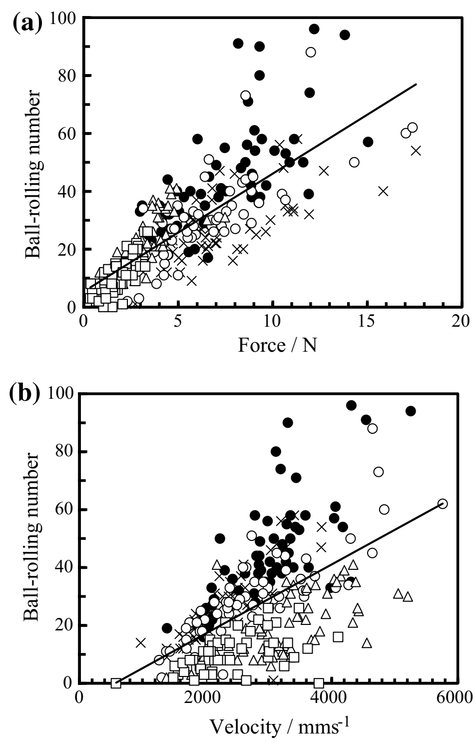

Fig. 3 The relationship among the maximum resultant force F (**a**), the maximum velocity of the stick (**b**) and the number of rolls. The *solid line* is a linear approximate *straight line* obtained from all data: *filled circle* finger; × stick length = 5 cm; *circle* 10 cm; *triangle* 50 cm; *square* 90 cm

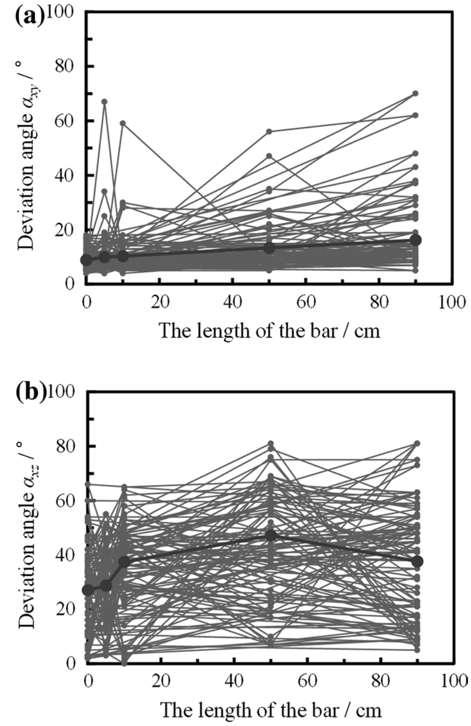

Fig. 4 The relationship between the deviation angle α_{xy} (**a**) or α_{xz} (**b**) and the length of the stick; *filled circle* the mean of 30 test subjects; *filled circle* data for each test subject

least-square method were 3.312, and the P value was 0.021. When conducting a two-sided test for probability = 0.05, the null hypothesis was dismissed for this factor.

The relationship between the maximum resultant force F or the maximum velocity v_s of the stick and the number of rolls are shown in Fig. 3a, b, respectively. A correlation coefficient between the number of ball rolls and F was 0.788, with which a relatively strong and positive correlation was observed. On the other hand, the correlation coefficient between the number of rolls and v_s was 0.578. From these results, it became clear that the greater power applied to the ball and the higher speed of motion of the stick resulted in the larger number of rolls. In Fig. 3a, b, furthermore, the gradient of the rolling velocity for F and v_s obtained when the ball was rolled with a finger was larger than that obtained when the ball was rolled with a stick. This means that a finger can roll the ball more frequently than a stick, when it is rolled by the similar force and velocity.

Furthermore, it was verified that the deviation angle has a significant impact on the number of rolls. The relationship between the length of the stick and the deviation angles α_{xy} or α_{xz} is shown in Fig. 4. $\alpha_{xy} = 8.9° \pm 3.2°$ was shown in the case of the finger, whereas α_{xy} increased with the length of the stick, and thus, $\alpha_{xy} = 16.2° \pm 13.2°$ when the stick is 90 cm long. On the other hand, while the deviation angle α_{xz} was $27.1° \pm 15.8°$ in the case of a finger, it was 29°–38° in the case of a stick. T and P values were 18.519 and <0.001, respectively, for the gradient b of the relationship between the deviation angle α_{xy} and the length of the stick for which the null hypothesis was dismissed, whereas they were 1.300 and 0.250, respectively, for the

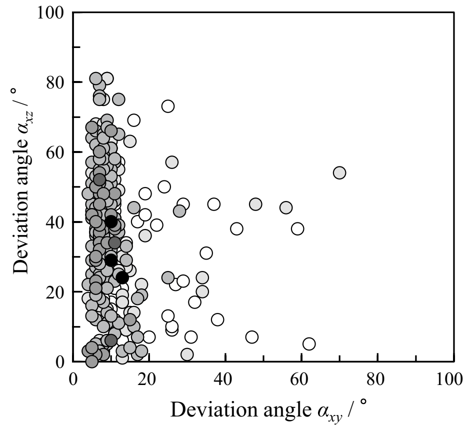

Fig. 5 The relationship between the deviation angle α*xy* or α*xz* and the number of rolls of the ball: the number of rolls = 0–10 times (), 11–20 times (), 21–40 times (), 41–60 times (), 61–80 times () and 81–100 times ()

deviation angle α_{xz}, for which the null hypothesis was not dismissed.

4 Discussion

This study found that the number of ball rolls decreased as the length of the stick increased. It was apparent that, since the number of rolls showed the same tendency as the maximum resultant force *F* applied to the ball and the maximum velocity v_s of the stick, both the velocity of the stick and the resultant force applied to the ball decreased as the length of the stick increased and thus the number of rolls decreased. In addition, an interesting trend was observed in the deviation angle α_{xy} of the stick for the rolling directions of the ball as well. That is, α_{xy} was always 20° or less when the number of rolls was 41 or more, whereas the number of rolls was always 20 or less when α_{xy} was 40° or more (Fig. 5). Considering that there was a positive correlation between the length of the stick and α_{xy}, we can speculate that the dispersion of the energy occurs due to the deviation of the stick direction from the ball-rolling direction as the stick becomes longer, and therefore, the number of rolls becomes smaller.

One of the findings to be noted is that a difference in performance occurred when using the stick and when not using it, regardless of its length. When the ball was rolled with a finger, the mean number of rolls was a maximum of 44.5 ± 18.8, and additionally, the number of rolls was never less than 15 (Fig. 2). On the other hand, when a stick was used, some trials were observed wherein the number of rolls was extremely small regardless of the length of the stick. These results suggest that the touching of the ball directly with a finger enables the precise control of the motion of the finger to prompt the rolling, thereby lowering the failure probability.

5 Conclusion

When a human rolls a ball with a stick, the number of rolls decreases as the stick became longer. Interestingly, the number of ball rolls increased with the force applied to the ball and the maximum speed of the stick, and additionally, it was affected by the deviation angle α_{xz} of the resultant force applied to the ball. Furthermore, it was shown that a task performed with a finger enabled more precise control of the motion due to direct contact to an object, and therefore results in greater success. Our results show that while a long stick is useful for operating remote objects, it is also a difficult tool to master, even for humans.

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