Investigation of Food Characteristics Modulating Spoon Motions in Skilled Spoon Users: Proposal of a Control Target for the Active Self-feeding Spoon

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Abstract  The present study proposes control targets for the motion of an active self-feeding spoon by analyzing skilled spoon motions reflecting the grasping actions of healthy people eating specific foods. We measured spoon motions in terms of time (t), rotational (θ) and azimuthal angles (φ) while five healthy participants ate soup, malt balls, firm tofu, pudding, and yogurt. We developed a wireless angle measurement spoon with which to evaluate changes in the inclination angles (IAs) of the spoon and the correlation between θ and φ during scooping and transporting spoon motions. A negative θ value indicates that the surface of the spoon bowl has rotated toward the participant. A negative φ value indicates that the tip of the spoon bowl has rotated downward. After observing eating actions and measuring IAs (θ, φ, t), we examined the correlation between θ and φ using the coefficient of determination R² with a second-order curve regression (2OCR) model. R² of the scooping action exceeded 0.55 while that of the transporting action was less than 0.25. We found the effects of food type on the grasping action as follows. For soup, the scooping and transporting times were longer than those for the other foods. The spoon was rotated negatively to avoid spilling soup and malt balls at the end of scooping and at the start of transporting. Firm tofu and pudding required cutting and scooping actions. The grasping action of food at the end of transporting affected the IAs (θ, φ). The correlation R of the relationship between the 2OCR model for pudding (R² = 0.79, highest among food types) and the 2OCR models for other foods exceeded 0.94. We suggest the control target of the active self-feeding spoon as follows: set IAs (θ, φ, t) at the start and end of scooping and transporting actions to avoid spillage induced by the inertial force of foods and to facilitate putting food into the mouth. IAs (θ, φ, t) during the scooping and transporting actions were applied to the 2OCR models for pudding (highest R²) and liquid food.

Keywords: grasping action, types of food, inclination angles of spoon.


1. Introduction
The ability of handicapped or disabled people to independently feed themselves is important and can reduce stress on both caregivers and care-receivers. Feeding support is important to maintain the motivation to eat and avoid malnutrition [1, 2]. Several types of passive self-feeding devices and full feeding assistance devices have been developed [3–7].

Recently, an active self-feeding (ASF) spoon that vibrates by itself to avoid spillage of food has been developed for users having difficulty adapting to a passive self-feeding spoon. As representative ASF spoons, Liftware Steady and Liftware Level support people with hand tremors and limited hand motion to feed in a dignified manner [7]. Liftware Level adapts to unintended movements of the hand, maintaining the spoon level when scooping and transporting food. However, mentally handicapped people may spill food more frequently during scooping and transportation because they do not understand the differences in rheological properties of foods. We have developed an ASF spoon for mentality handicapped people [8]. Mechanical and electrical constructions are almost the same as those of the Liftware Level, but we consider the control method of the ASF spoon for the mentally handicapped person. We investigated the rotational angles (IAs) of the spoon [9]. The rotational angle (θ) is defined as the roll angle while the azimuthal angle (φ) is defined as the pitch angle, both
being centered on the grip of the spoon. We confirmed that liquid food was the most easily spilled food type, and that spillage was related to the shape of the spoon bowl and the mass of the scooped food. Spillage depends not only on the IAs but also on the inertia force induced by acceleration of the spoon and the posture of the head for putting the spoon into the mouth. According to the age-related movement ability of the upper limbs, the use of a spoon differs between holding a spoon in the palm during early childhood and pinching a spoon with the fingers in adulthood through trial and error [10]. We thus consider empirically mastered spoon motion as the target of control of the motion of the ASF spoon.

The present study proposes a control target for the motion of an ASF spoon through analysis of skilled spoon motions of healthy people eating specific foods, focusing on the time (t) change of IAs ($\theta$, $\varphi$, t). The types of food tested were liquid, solid (firm and soft), small solid particles and gel. IAs ($\theta$, $\varphi$, t) were measured wirelessly when five healthy participants ate the five types of food. Meanwhile, previous studies have reported that feeding by tool or by hand can be evaluated by dividing the process into (1) holding or scooping the food with a tool or by hand, and (2) transporting the food to the mouth [11–14]. Likewise, in our study, spoon motion was divided into scooping and transporting actions to investigate the effect of food type on the grasping action for the spoon motions. To investigate the effect of food type on the grasping action for spoon motions, we first evaluated statistical differences in the required time and the starting and ending IAs ($\theta$, $\varphi$, t) for scooping and transporting of different food types. The effect of the person’s habit on the spoon motion was then evaluated by the correlation between $\theta$ and $\varphi$ for all participants using the coefficient of determination $R^2$ with curve fitting for each type of food. The similarity of the spoon motion pattern was evaluated by the correlation $R$ of the relationship between the curve-fitting model for the food type least affected by the person’s feeding habit and the models of other food types; i.e., the relationship between the curve-fitting model with the highest $R^2$ and the models of other types of food. Finally, we propose a control target of the ASF spoon for scooping and transporting of food using the characteristics of IAs ($\theta$, $\varphi$, t) to consider the grasping action.

2. Methods

2.1 Participants

Five healthy volunteers (aged 20 years, right handed) participated in this study. All participants provided written informed consent before commencing the experiments. The study protocol (H26–02) was approved by the ethics committee of Tokyo National College of Technology.

2.2 Measurement spoon with improved sensitivity to inclination angles

Figure 1 shows the improved wireless angle measurement spoon (IWAMS) and a commercially available self-feeding spoon. With the IWAMS, it is possible to measure temporal changes in the IAs. The IWAMS includes a wireless angle measurement module (WAMM) and a commercially available spoon (Figure 1a). The IAs include the azimuthal angle $\varphi$, the rotational angle $\theta$, and the time t. The WAMM, which is attached to the handle of a commercially available spoon with rubber and

![Fig. 1](image-url) IWAMS and a self-feeding spoon. (a) IWAMS is composed of a commercially available spoon and WAMM and (b) handling of the IWMSAS and the self-feeding spoon.
double-sided tape, comprises a printed electrical circuit board, a peripheral interface controller (PIC) microcomputer (Microchip Technology, 16F887), a Li-Po battery (SparkFun, PRT-00731), a power regulator circuit (SparkFun, PRT-11231), a Bluetooth module (Microchip Technology, RN42XVP-1/RM), and digital output signal of a three-dimensional accelerometer (3DA) (Freescale Semiconductor, MMA8451Q). We estimate $\varphi$ and $\theta$ using the 3DA data received. The output voltage of the 3DA is transmitted from the PIC computer to a personal computer (PC) via Bluetooth. The PC estimates and records the IAs ($\theta, \varphi, t$) in real time. The total weight of the IWAMS, including the 35 g spoon and the 30 g WAMM, is 65 g. The weight and size of the IWAMS is similar to that of a commercially available self-feeding spoon (Figure 1b). Thus, it is unlikely that the weight and size of the IWAMS would interfere with daily feeding spoon motions. Figure 2 shows the output voltages of the 3DA (Figure 2a) and the definitions of rotational direction for $\varphi$ and $\theta$ (Figure 2b). Figure 2a demonstrates the original coordinates of the output voltages ($V_X$, $V_Y$, and $V_Z$), and the output voltage of the declined 3DA in the handle of IWAMS. For example, the output voltages of the 3DA are $v_x$, $v_y$, and $v_z$ when the 3DA declines to $-\varphi$ and $-\theta$. The relationship between the output voltages and the IAs ($\theta, \varphi$) deg is defined as follows:

$$
\theta = \frac{180}{\pi} \tan^{-1} \frac{v_y}{v_z}, \quad \varphi = \frac{180}{\pi} \sin^{-1} \frac{v_x}{v_g}
$$

(1)

where $v_g$ is $\sqrt{v_x^2 + v_y^2 + v_z^2}$. Both angles are calculated from Eq. 1. The range of calculated angles from $-180 < \theta(\varphi) < 180$ deg is corrected on the PC by confirming the negative or positive sign of each output voltage.

As shown in Figure 2b, the rotational angle of the spoon is denoted $\theta$, with the counterclockwise direction having a negative value. The azimuthal angle is denoted $\varphi$, with the counterclockwise direction having a negative value. The specifications of the IWAMS are as follows: the correlation $R$ between the image processor and predicted angles of IAs ($\theta, \varphi$) is greater than 0.97, and the root mean square indicating measurement repeatability is $\pm 1.5$ deg. The evaluation method for IWAMS performance has been published elsewhere [8].

2.3 Experimental setup

Figure 3 shows the experimental setup. Figure 3a shows the experimental apparatus and the physical relationship between the participant and the food dish. The participant sat at a table with a width of 0.6 m, length of 0.4 m, and height of 0.76 m. He sat on a chair with a seat height of 0.47 m. The distance from the bowl to the participant was adjusted such that the bowl was located beneath the center of the palm of the participant’s outstretched dominant hand (right). The participant was allowed to freely position the non-dominant hand. However, the participant was asked to avoid touching the bowl. To examine the relationship between spoon motion and the kinematics of the lower arm, we captured eating motion using three CCD-cameras (IPX-VGA120, IMPERX) controlled by a desktop PC. We discriminated scooping from transporting actions by visual inspection of the recorded images in three directions. The start and end times of scooping action were defined as the moment when the spoon was first placed into the bowl and the moment when the spoon left the bowl, respectively. The start and end times of the transporting action were defined as the moment when the spoon left the bowl and the time when the spoon entered the mouth of the participant. Images were captured at intervals of 0.03 s, generated by a function generator (AD8624A, A&D). This interval was as same as that for data transmission from the IWMAS.

2.4 Food types

All the foods were placed into identical bowls. The eating motions were performed three times for each type of food. We used the third trial of each eating motion for IAs analysis ($\theta, \varphi, t$), as we expected that participants

![Fig. 2](image-url) Definitions of rotational directions of IAs ($\theta, \varphi$) and output voltages of the 3DA in the IWAMS. (a) Relationship between IAs ($\theta, \varphi$) and output voltages ($v_x, v_y, v_z$) of 3DA. (b) Definitions of the inclination directions of IAs ($\theta, \varphi$).
would be more familiar with the eating movements after repeating several times. The trials for analysis satisfied the following conditions. The participant scooped an appropriate volume of food, separated the food easily, and successfully scooped up the food without spilling. The difference in friction between different types of food and the surface of the spoon contributed to the varying degree of difficulty of the above actions. The liquid food was soup. The solid foods were malt balls (small solid particles), firm tofu (firm solid), and pudding (soft solid). The yogurt was gel.

Figure 3b shows the five types of food in the bowl. We measured temporal changes in IAs ($\theta$, $\phi$, t) during scooping and transporting actions.

2.5 Data analysis

The statistical differences among the times taken to perform scooping and transporting movements for each food type were analyzed and compared using the Tukey-Kramer multiple comparisons test (JMP, SAS Institute Inc.). The results are shown as mean ± standard deviation (SD). Statistical significance was defined as $p < 0.05$. Individual differences in spoon motion were investigated according to variations in the time (SD) spent in scooping and transmitting motions for each type of food. When scooping solid food, it was necessary to first cut the food using the spoon. Thus, we estimated that during scooping, the spoon would be held in a declining position such that the rotational angle of the spoon would be adjusted widely from the negative ($-\theta$) to positive ($+\theta$) directions, depending on the characteristics of food. Additionally, we estimated that when scooping the food from the bowl, the spoon tip would be adjusted narrowly in a declining position within the negative direction ($-\phi$).

We examined the IAs ($\theta$, $\phi$, t) of scooping and transporting actions in terms of the correlation between $\theta$ and $\phi$ using the coefficient of determination ($R^2$) with a 2nd order curve regression (2OCR) model ($\phi = a\theta^2 + b\theta + \gamma$).

The data resolution of the three-dimensional acceleration sensor (digital output) was 14 bits ($-8192$ to $8192$ div) against $\pm 180$ deg. The measurement resolution was $180$ deg/$8192$ div = $0.02$ deg/div. We therefore considered that the effect of measurement resolution on $R^2$ was weak.

3. Results

3.1 Participants behavior

Figure 4 shows an example of the IAs ($\theta$, $\phi$, t) over time. As mentioned, we distinguished scooping from transporting motions by visual inspection of the captured images. We did not observe re-scooping action in any trial. Three participants (A, B, and E) placed the non-dominant hand on the thigh. Two participants (C and D) placed the non-dominant hand on the table. Visual inspection indicated that the position of the non-dominant arm remained steady, and that there were no unnatural body movements. Thus, the position of the non-dominant arm appeared to have minimal effect on the data. When scooping food from the bowl, the participants...
started by inclining the spoon tip downward (corresponding to a negative $\varphi$) with the spoon surface rotated toward them (corresponding to a negative $\theta$) (Figure 2a).

3.2 Scooping action
Figure 5 shows temporal changes in the scooping IAs ($\theta_S$, $\varphi_S$, t) and the 2OCR model of $\theta_S$ and $\varphi_S$ for all foods and participants. S and E indicate the start and end, respectively, of the scooping motion for the five participants represented by different symbols. Figure 5a shows the IAs of the scooping action ($\theta_S$, $\varphi_S$, t) for all foods and participants. Both $\theta_S$ and $\varphi_S$ simultaneously changed from negative values at the start of the scooping action to positive values at the end of scooping. For all participants except participant E, the scooping time for soup was the longest among all types of food; this scooping time exceeded 3 s. In the case of participant E, the scooping time for soup was approximately the same as that for yogurt: 3.6 s. The scooping action for pudding resembled either that for soup (participants C and E) or that for firm tofu (participants A, B, and D). The time spent engaged in the scooping action increased when the spoon bowl was kept level. The scooping action for yogurt also resembled that for soup (participants D and E) or that for firm tofu (participants A, B, and C). In the case of participant E, $\theta_S$ remained constant when scooping yogurt, such that only $\varphi_S$ changed. Figure 5b and Table 1 show the R$^2$ for $\theta_S$ and $\varphi_S$ obtained with the 2OCR model for each food. The dispersion patterns of the scatter plots of IAs ($\theta_S$, $\varphi_S$) were categorized into a group consisting of soup and malt balls and a group consisting of other foods. R$^2$ for the relation between the 2OCR model and scatter plots exceeded 0.55, indicating moderate or strong correlation. Figure 6 presents the effects of food type on the scooping time and IAs at the start and end of scooping ($\theta_S$, $\varphi_S$). The scooping time for liquid food involved a longer transporting time, lower R$^2$ for the 2OCR model of $\theta_T$, $\varphi_T$, $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant. Figure 7a shows the IAs ($\theta_T$, $\varphi_T$, t) and the 2OCR models of $\theta_T$ and $\varphi_T$ for all foods and participants. S and E indicate the start and end, respectively, of the transporting motion for each participant.

4. Discussion
4.1 Method of holding a spoon
Rosen et al. [15] investigated the effects of different methods of holding a spoon on the kinematics of upper-limb motion. The methods of holding a spoon were normal hand grasping (sandwiching the spoon between two fingers with support by the thumb) and power grasping including the wrist (holding the spoon in the palm). They confirmed that the movable region of the wrist for normal hand grasping was half of that for power grasping along with the wrist. We assume that the method of holding the spoon with normal hand grasping, which involves not only action of the wrist but also action of the fingers, was able to realize a steady posture of spoon motion during scooping and transporting. The method of holding a spoon in this study was normal hand grasping in all participants and there was no re-scooping or stopping during scooping and transportation. We therefore considered that the method of holding the spoon had little effect on the spoon motion.

4.2 Relationship between the feeding motion and grasping action
Quinlan et al. [12] showed that the feeding action (holding and transporting food) with a tool (such as a fork) involved slower hand movements and took longer than feeding by hand. They found that feeding action with a tool had a lower maximum velocity and longer duration when the volume of cube-shaped food increased. They suggested that the decrease in maximum velocity and increase in duration of the feeding action of holding food and putting the tool into the mouth resulted from a need for high accuracy. Kamp et al. [13] investigated the grasping action of transporting liquid and solid foods with a spoon. They reported that the grasping action for liquid food involved a longer transporting time, lower
Fig. 5  Scooping action for the five health participants while scooping soup (liquid), firm tofu (hard solid), pudding (soft solid), malt balls (small solid particles) and yogurt (gel). (a) Temporal changes in IAs ($\theta_S$, $\varphi_S$, t) and (b) correlation of IAs ($\theta_S$, $\varphi_S$) analyzed with 2OCR model. S and E indicate the start and end, respectively, of scooping action for the five participants represented by different symbols.
acceleration and deceleration, and lower maximum velocity compared to solid food. They also confirmed that the grasping action was related to not only the velocity of the spoon but also the displacement of the head and degree of movement of the elbow. From these investigations of grasping action, we assume that the IAs ($\theta, \varphi$) measured in this study can be used to identify the characteristics of the grasping action by analyzing the temporal changes in IAs ($\theta, \varphi, t$). We investigated the control targets of the ASF spoon for scooping and transporting actions according to the time required, the IAs ($\theta, \varphi$) at the start and end, and the time course of IAs ($\theta, \varphi$).

4.3 Scooping action

We discuss the control target of the ASF spoon during the period of scooping. Kamp et al. [13] reported that the grasping action of transporting liquid food took longer than the grasping action of transporting solid food. We hypothesize that the grasping action of participants for different types of food affects not only the transporting action but also the scooping action. Figure 6 shows that the scooping time for liquid food was significantly longer than those of other foods with the exception of yogurt ($p < 0.05$). The SD of the scooping time for the gel food was slightly greater than that for the liquid food. We thus suggest that all participants recognized that liquid food was the easiest to spill and they slowed their spoon use when scooping. We consider that the large SD in the scooping time produced individual differences in the grasping action for solid and liquid foods. There were no significant differences in IAs ($\theta_S, \varphi_S$) at the start of scooping among the types of food. The rotational angle of the spoon tended to increase when scooping solid food that required cutting to separate from the remaining food. Osaki et al. [16] also reported that the rotational angle $\theta_S$ of a spoon was greater for solid food than for liquid food at the start of scooping. Meanwhile, there was no significant difference in $\varphi_S$ at the start of scooping among the various types of food. We served all foods in a small deep bowl so that all users had to orient the tip of the spoon downward when putting the spoon into the bowl (Figure 9). We suggest that $\varphi_S$ at the start of scooping was affected by the shape of the bowl rather than the type of food. We thus suggest that the grasping action for various food types at the start of scooping is almost related to $\theta_S$.

In the cases of liquid and small solid particles, the $\theta_S$ at the end of scooping had a negative value. The $\theta_S$ for the

<table>
<thead>
<tr>
<th>Food (Food Type)</th>
<th>2OCR model of scooping action ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soup (Liquid)</td>
<td>$\varphi_S = 0.0048 \theta_S^2 + 0.7861 \theta_S - 0.8269$ (0.58)</td>
</tr>
<tr>
<td>Malt balls (Small solid particle)</td>
<td>$\varphi_S = 0.0031 \theta_S^2 + 0.6220 \theta_S - 2.8960$ (0.76)</td>
</tr>
<tr>
<td>Firm tofu (Firm solid)</td>
<td>$\varphi_S = 0.0044 \theta_S^2 + 0.6276 \theta_S - 14.590$ (0.78)</td>
</tr>
<tr>
<td>Pudding (Soft solid)</td>
<td>$\varphi_S = 0.0030 \theta_S^2 + 0.5474 \theta_S - 9.1859$ (0.79)</td>
</tr>
<tr>
<td>Yogurt (Gel)</td>
<td>$\varphi_S = 0.0046 \theta_S^2 + 0.6474 \theta_S - 10.784$ (0.55)</td>
</tr>
</tbody>
</table>

Fig. 6 Effects of food type on IAs of the spoon and time taken for the scooping action ($n = 5$).
Fig. 7  Transporting action for the five healthy participants while transporting soup (liquid), firm tofu (hard solid), pudding (soft solid), malt balls (small solid particles) and yogurt (gel). (a) Temporal changes in IAs ($\theta_T$, $\phi_T$, $t$) and (b) correlations of IAs ($\theta_T$, $\phi_T$) analyzed using 2OCR model. S and E indicate the start and end, respectively, of transporting action for 5 participants represented by different symbols.
liquid and small solid particles were significantly different from that for the firm solid. Meanwhile, the $\phi_S$ at the end of scooping was almost zero for all food types, and there was no significant difference among the foods. We thus confirmed that the effect of the $\phi_S$ on the grasping action at the end of scooping was small. The negative direction of the $\theta_S$ of the spoon (declined angle of the spoon relative to the moving direction) prevented spillage due to the inertial force of the spoon’s motion [9, 17]. We suggest that all participants recognized that the liquid and small solid particles spill easily and that they subsequently diminished the rotational angle of the spoon relative to the moving direction when transporting these foods.

Quinlan et al. [12] and Kamp et al. [3] presented that feeding motion that recognized the grasping action was displayed that the temporal change in velocity indicated the curve with the maximum velocity and the occurrence of maximum velocity at the time ratio required moving time. We evaluated the effect of a person’s habit on the spoon motions based on the correlation coefficient ($R^2$) between the 2OCR model and scatter plot of IAs ($\theta_S$, $\phi_S$) for each type of food. We confirmed that $R^2$ exceeded 0.55 for all foods, indicating a moderate or strong relation (Table 1). A comparison of the 2OCR models for firm tofu versus soup and firm tofu versus small solid balls revealed a large difference in initial values ($\gamma$) but little difference in coefficient. The $\theta_S$ of the spoon at the end of scooping was significantly different between firm tofu and soup and between firm tofu and malt balls (Figure 6). We thus assume that the relationship between the IAs ($\theta_S$, $\phi_S$, $t$) during the course of scooping might become constant, with no effect of food type on the spoon motion. We investigated the similarity of the spoon motion pattern by analyzing the correlation $R$ of the relationship between the 2OCR model with the highest $R^2$ and the models of other types of food. We obtained the similarity (correlation) $R$ between the 2OCR model of

<table>
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</thead>
<tbody>
<tr>
<td>Soup (Liquid)</td>
<td>$\phi_T = -0.0090\theta_T^2 + 0.0500\theta_T - 2.4878 (0.08)$</td>
</tr>
<tr>
<td>Malt balls (Small solid particle)</td>
<td>$\phi_T = 0.0076\theta_T^2 + 0.0876\theta_T - 2.9737 (0.003)$</td>
</tr>
<tr>
<td>Firm tofu (Firm solid)</td>
<td>$\phi_T = 0.0014\theta_T^2 + 0.0622\theta_T + 7.5604 (0.01)$</td>
</tr>
<tr>
<td>Pudding (Soft solid)</td>
<td>$\phi_T = -0.0161\theta_T^2 + 0.2452\theta_T + 4.7528 (0.09)$</td>
</tr>
<tr>
<td>Yogurt (Gel)</td>
<td>$\phi_T = 0.0008\theta_T^2 + 0.4657\theta_T + 3.2173 (0.25)$</td>
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</table>

Fig. 8 Effects of food type on IAs of the spoon and time taken for transporting action ($n=5$).
foods. were set to be identical to have an equal range for all
was the most easily spilled food type. The IAs (θ)
pants in the present study recognized that liquid food
icant difference between soup and other foods is similar
scooping action of soup. Thus, the relationship of IAs
er that the cutting action of firm tofu also serves as the
sion depends on the type of food. For example, the IAs
control target of the ASF spoon when scooping food
marizing the above findings, we suggest the following
Fig. 10 Evaluation of similarity between the 2OCR model
pudding with the highest R² and that of other foods:
\[ R = \frac{\sum_{k=1}^{n}(x_k - \bar{x})(y_k - \bar{y})}{\sqrt{\sum_{k=1}^{n}(x_k - \bar{x})^2} \sqrt{\sum_{k=1}^{n}(y_k - \bar{y})^2}} \] 
where \( k \) is the data number ranging from 0 to \( n \), \( x_k \) is \( \phi_k \)
of the 2OCR model estimated for each food, \( \bar{x} \) is the mean value of \( \phi_k \)
for each food, \( y_k \) is \( \phi_k \) estimated for the 2OCR model of firm tofu, and \( \bar{y} \) is the mean value of \( \phi_k \)
for firm tofu. The rotational angles \( \theta_k \) at the start and end
were set to be identical to have an equal range for all
foods.

We confirmed that R of the relationship among pudding and other foods exceeded 0.94 (Figure 10). Summarizing the above findings, we suggest the following control target of the ASF spoon when scooping food while considering human articulation. The grasping action depends on the type of food. For example, the IAs (θ₁, φ₁) are changed to cut food at the start of scooping and to prevent spillage during transportation. We consider that the cutting action of firm tofu also serves as the scooping action of soup. Thus, the relationship of IAs (θ₁, φ₁) during scooping of soup almost coincides with that during scooping firm solid food in the 2OCR model.

4.4 Transporting action
We discuss the control target of the ASF spoon during the transportation of food. Figure 8 confirms significant differences in the transporting time between soup and other food types (p < 0.05). We suggest that the significant difference between soup and other foods is similar to that reported by Kamp et al. [13], in that all participants in the present study recognized that liquid food was the most easily spilled food type. The IAs (θ₁, φ₁) at the start of transportation were similar to those at the end. We confirmed that there was a grasping action at the start of transportation. In terms of the final IAs (θ₁, φ₁), θ₁ was negative for all types of food and φ₁ was larger for firm tofu and pudding than for other types of food. In general, feeding is an action that involves not only the upper limb but also of the head [14]. Kamp et al. [13] indicated that the grasping action at the time of putting a spoon into the mouth was related to displacement of the head. The displacement of the head for fluid food was greater than that for solid food. Quinlan et al. [12] reported that the tool grasping action during transportation is affected by the size of food. The contact pressure between the lower lip and the spoon increased when placing food in the mouth as the depth of the spoon bowl increased [18]. It was found that the grasping action of putting food into the mouth induced not only a temporal change in velocity of the tool but also affected the movement of the upper limb and head. We thus consider that IAs (θ₁, φ₁) at the end of transportation are interlocked with head movement and that the grasping action depends on not only the type of food but also on the size of food. To evaluate the effect of a person’s habit on the spoon motions, we investigated the correlation R² between the 2OCR model and scatter plot of IAs (θ₁, φ₁) for each type of food. We confirm that R² was less than 0.25 for all types of food, indicating a weak relationship (Table 2). A weak correlation between IAs (θ₁, φ₁, t) was observed during transportation, indicating that the spoon motion during transporting action should take into account potential spillage induced by the relationship between the shape of the spoon and the IAs (θ₁, φ₁, t) and the inertial force of food. Summarizing the above findings, we suggest the following control target for transporting action using the ASF spoon. First, set the IAs (θ₁, φ₁) at the start of transportation to avoid spillage due to the inertial force of food. Next, apply IAs (θ₁, φ₁, t) to, for example, the 2OCR model of fluid food. Finally, adjust IAs (θ₁, φ₁, t) at the end of transportation according to the type and mass of food to facilitate placing food into the mouth.

4.5 Future work
Considerations for future research are as follows. To apply the proposed control target to the ASF spoon, the ASF spoon itself needs to recognize the type of food and the required spoon motions such as scooping and transportation. The diameter of the grip of the spoon affects the range of wrist motion [16]. We therefore need to develop an ASF spoon with consideration of the size of the spoon grip and to assemble sensors for the identification of the orientation of the spoon and for distinguishing scooping and transporting actions. In future work, it may be possible to measure the direction of the spoon tip by distinguishing scooping and transporting actions. We plan to continue developing the IWMAS such that it will
be able to distinguish scooping and transporting spoon motions. Foods have variable rheological properties that affect swallowing and eating. The spoon motions used to scoop and transport yogurt were variable in the present study. Thus, the rheological properties of yogurt appear to indicate that it is not easily spilled and is easy to eat. An important topic of research in meal support is the issue of pulmonary aspiration. We hope to investigate the relationship among food properties, ease of scooping, and safety in feeding.

5. Conclusion

By measuring the motions of IWMAS spoon that participants used to eat a liquid food (soup), small-particle food (malt balls), firm solid food (firm tofu), soft solid food (pudding), and gel food (yogurt), we found that the typical patterns of spoon motion were different for liquid and solid foods. The grasping actions employed for easily spilled foods (liquid food and small solid particles) compared with those used for solid foods were presented in terms of IAs (θ, ϕ) at the start and end of scooping and transporting actions. The IAs (θ, ϕ, t) during scooping and transporting food did not depend on the type of food. The IAs (θ, ϕ) of the 2OCR model during scooping and transporting actions were applied to, for example, soft solid and fluid foods.

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Conflict of Interest

The authors declare no conflicts of interest.

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