Quantitative Comfort Evaluation of Eating Assistive Devices based on Human Effort Estimation using an Accelerometer

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***Abstract*— Robot usage in the fields of human support and healthcare is expanding. Robotic devices to assist humans in the self-feeding task have been developed to help patients with limited mobility in the upper limbs but the acceptance of these robots has been limited. In a previous work, we proposed to quantitatively evaluate the comfort of an eating assistive device by estimating the interaction forces between the human and the robot when eating. In this work, we investigate how to quantitatively evaluate the comfort by estimating the human effort when eating. With a similar approach, we use an inexpensive accelerometer to estimate the human effort from the acceleration of the human torso during the feeding process. We experimentally verify our concept with a commercially-available eating assistive device and human subjects. The evaluation results demonstrate the feasibility of our approach.**

I. Introduction

The robotic applications in the healthcare field are increasing due to the insufficient number of healthcare workers to match the demand, especially in countries with large aging societies. One of these applications is the human feeding task since many patients have difficulties lifting or using their limbs (*e.g.*, uncontrollable movements). For these patients with upper-limb disabilities, proper eating is very important to maintain their motivation and avoid malnutrition [1].

Eating assistive devices are a viable option to support the food ingestion of patients and relieve the load of the healthcare personnel. Thanks to the development of robot technology, various eating assistive devices have been developed [2], [3], [4], [5], [6]. Most of such devices consists of a robot arm equipped with eating utensils, such as spoons, to take food from a plate and put it in or in front of the patient's mouth. Depending on the level of disability of the target patients, these devices are designed to take the food automatically or semi-automatically.

Nevertheless, the existing eating assistive devices have suffered from a limited acceptance by the users. We consider that this is caused by multiple factors influencing the user's comfort when using an eating assistive device such as the amount of food per bite, the eating pace, and the food-delivery location.

As we tend to naturally minimize our effort when executing motions in general, it is conceivable that we minimize the effort to get the food from the spoon when eating. Nevertheless, a smooth eating process cannot be achieved if the spoon is in a location that is hard to reach, from an anatomical point of view. In such cases, the user's ability to accurately control the motion decreases due to an atypical posture, which negatively impacts the user's comfort.

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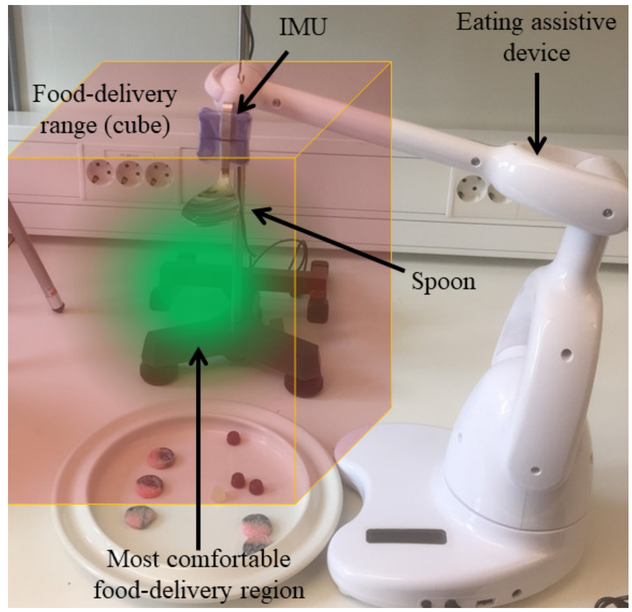

Fig. 1: Comfort of an eating assistive device. An IMU on the human torso is used to estimate the human effort and an IMU on the robot spoon is used to estimate the interaction force when eating. Regions with lower interaction force and human effort are more comfortable.

In our previous work [7], we investigated how to quantitatively evaluate the comfort of an eating assistive device by measuring the interaction forces present during the biting process (*i.e.*, when a human takes food from the spoon held by the robot). At that time, we estimated the interaction forces from an accelerometer placed on the spoon.

In this study, we propose to quantitatively evaluate the comfort of an eating assistive device by estimating the human effort during the biting process. In particular, we investigate the influence of the food-delivery location as a factor that affects the user's comfort. We consider that comfortable eating is characterized by less human effort present during the biting process, as depicted in Fig. 1.

We propose to use an accelerometer to estimate the human effort during feeding. Since the accelerometer is easy to attach, the proposed method can be applied anytime. Another advantage is that accelerometers are considered more affordable than other types of sensors such as force sensors and much less sensitive to privacy-related issues.

We test our concept with a commercially-available eating assistive device of the type that places the food in front of the user's mouth. We record the acceleration data from an accelerometer placed on the human torso and use it to estimate the human effort when eating. We also show the food-delivery locations which present less human effort, and compare the results to the quantitative comfort evaluation from our previous work which uses the data from an accelerometer mounted on the spoon.

It is worth noting that, in this paper, we are following an experiment-based approach rather than a model-based approach. We study the data from the accelerometer placed on the human torso to estimate the human effort. As a first approach, we assume that the less smooth the human motion to reach the spoon is, the less comfortable the device is for the user.

The rest of the paper is organized as follows. Section II mentions the related works. Section III describes the proposed method. Section IV presents the experiments and the obtained results. Finally, Section V concludes this paper and presents some directions for future work.

II. Related Works

Previous research includes intelligent control of eating assistive devices for people with highly-limited mobility [8] and dynamics simulation of the mutual force between mouth and spoon [9]. The present study aims to quantitatively evaluate the comfort of eating assistive devices using a simple accelerometer, which is practical and applicable to even closed-source, commercially-available eating assistive devices.

Park *et al.* have introduced a robot-assisted feeding system that delivers food inside the user mouth [10], [11], [12]. Although the authors are not evaluating comfort, they also measure forces to determine anomalous feeding. The anomalies are determined by measuring the difference between typically successful eating patterns and the ongoing eating process. This difference may also be connected to the discomfort but this has not been studied. In other words, the work from Park *et al.* focuses on monitoring the anomalies during the physical interaction, while the present study focuses on preventing the anomalies that may arise during such interaction.

Song *et al.* use a range detection sensor around the spoon of an eating assistive robot to control the position of the food-delivery location [13]. The authors consider that the spoon should be tilted to ease the food unload in the user's mouth. Though the spoon tilt can be considered as a strategy to increase the efficiency of the feeding, it is also related to the comfort of the subject since he/she can get the food more easily but the authors do not provide any quantitative evaluation of the user's comfort.

To minimize the cost, Bien *et al.* propose a method for sensorless measurement of the torque and force [14]. The authors implement a compliant control without any force or torque sensors, which relies in a cable-driven mechanism. Though this approach can be used to measure the force without expensive equipment, it has a limited applicability to commercially-available eating assistive devices.

III. Human Effort

When using an assistive device, humans need to bring their mouth from their current sitting pose to where the spoon is located. To do this, they use their torso muscles to reach for the spoon and retrieve the food.

Due to the anatomy of the human body, there are certain regions that are easier to reach from an ergonomical point of view. Reaching these regions require less muscle energy, *e.g.*, motions require fewer muscles. Though the distance from the mouth to the spoon affects how much muscle energy is necessary, we need to also consider how much the mouth trajectory differs from an ideal ergonomical motion. The bigger such difference is, the less smooth the motion is, and, hence, the more muscle energy the human spends.

We consider that the *human effort* is related to both the *smoothness* of the human motion and the *amount* of the human motion. In other words, the smoother and shorter the human motion is to reach the spoon and eat, the lower the human effort is and, therefore, the more comfortable the eating process is for the user.

We propose to estimate the human effort E as follows:

$$E \doteq \frac{m}{t_f - t_0} \int_{t_0}^{t_f} \|\mathbf{a}(t)\| \, dt \, , \tag{1}$$

where t_0 and t_f are the start and finish of the biting sequence, *i.e.*, from and back to a neutral sitting pose including the physical interaction between the human and the spoon, as exemplified in Fig. 2, $\mathbf{a}(t)$ is the acceleration measured by the accelerometer on the human torso, and m is the mass of the human torso, including head and arms. The human mass is computed from anthropometric data, or more concretely, from the normalized mass of body segments which can be found in the literature, *e.g.*, [15]. Here, the normalized mass of the human torso corresponds to the 67.8% of the body mass.

The human motion estimation is modeled in the manner of the temporal mean or the average value of a function to enclose the characteristics of the human motion when eating. This formulation of the human effort resembles to some extent that of the Head Injury Criteria (HIC) [16], which describes the likelihood of head injuries should an impact occur. Though HIC is usually measured for a short period of time (15 ms or 36 ms), our human effort estimation considers a longer period of time (3 to 5 s), which is the duration of a single eating sequence. The resulting units of the human effort are Newtons, which is useful for the purpose of evaluation and for a comparison to the interaction forces present during the biting process.

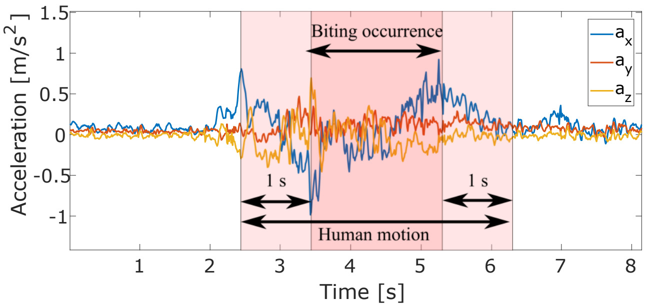

Fig. 2: Example of an eating sequence. The highlighted bars are the physical interaction with the spoon (biting occurrence) and the human motion from and back to a neutral sitting pose before and after eating, when the human effort is estimated.

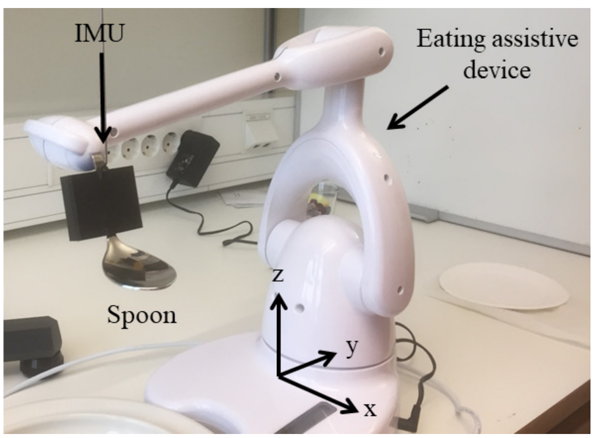

Fig. 3: Experimental setup (assistive device view). The assistive device has an accelerometer mounted near the spoon.

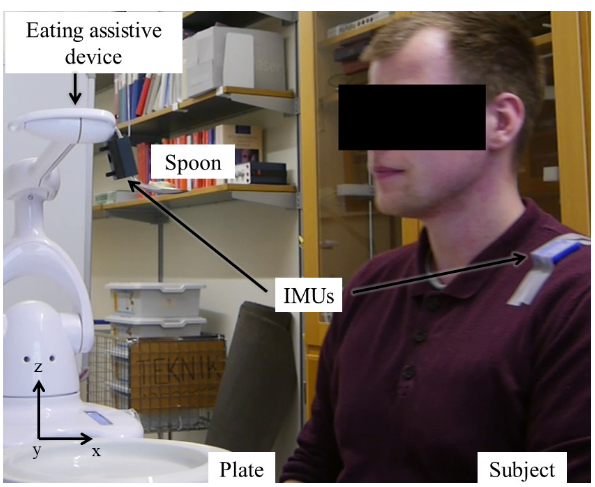

Fig. 4: Experimental setup (overall view). The human subject sits in front of the assistive device. One accelerometer is mounted near the spoon and another one is placed on subject's left shoulder.

TABLE I: Subjects and setup dimensions

Subject	Weight [m]	Height [m]	Mouth height [m]	Spoon height [m]	Relative height [m]	Depth [m]
A	90	1.8	0.304	0.2 0.3 0.4	0.104 0.004 -0.096	0, 0.05, 0.1
B	95	2.02	0.25	0.15 0.2 0.3	0.1 0.05 -0.05	0, 0.05, 0.1
C	55	0.82	0.355	0.3 0.36 0.42	0.055 -0.005 -0.065	0, 0.05, 0.1
D	86	1.85	0.347	0.2 0.3 0.4	0.147 0.047 -0.053	0, 0.05, 0.1
E	68	1.7	0.278	0.2 0.3 0.4	0.078 -0.022 -0.122	0, 0.05, 0.1

IV. Experiments and Results

A. Experimental Setup and Methodology

We use the commercially-available eating assistive robot *Bestic*[1] to experimentally verify our concept. This robot is capable of adjusting the height and depth of the food-delivery location. On the robot spoon and on the human torso, we installed the accelerometer LP-Research Motion Sensor Bluetooth version 2 (LPMS-B2[2]) which is a miniature wireless inertial measurement unit (IMU) with Bluetooth connectivity. The experimental setup is shown in Fig. 4.

We asked five healthy subjects in his 20s to eat banana slices placed on the spoon held by the robot. The food-delivery locations consisted of three heights and three depths on the xz-plane. The subjects ate three banana slices (one by one) at each food-delivery location so that we collected 27 samples per subject.

Before each experiment session, the accelerometer is calibrated so that the z-axis of its coordinate system is parallel to the gravity vector. The acceleration data provided by the accelerometer already accounts for the gravity (*i.e.*, acceleration is zero if the accelerometer is motionless).

B. Human Effort

We estimate the human effort during eating from the acceleration data obtained from an accelerometer mounted on his left shoulder and the human mass corresponding to the torso, including the arms and head. This mass was assumed to be the 67.8% of each subjects' body mass. The height of the subjects' mouths with respect to the table, the spoon height, the relative height of the user's mouth to the robot spoon height, as well as the weight and height of the subjects, are shown in Table I.

[1]Bestic. www.camanio.com/en/products/bestic/
[2]LPMS-B2. www.lp-research.com/lpms-b2/

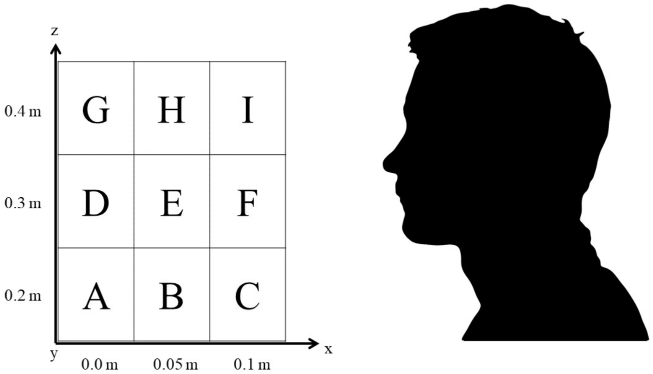

Fig. 5: Sketch of the food delivery locations.

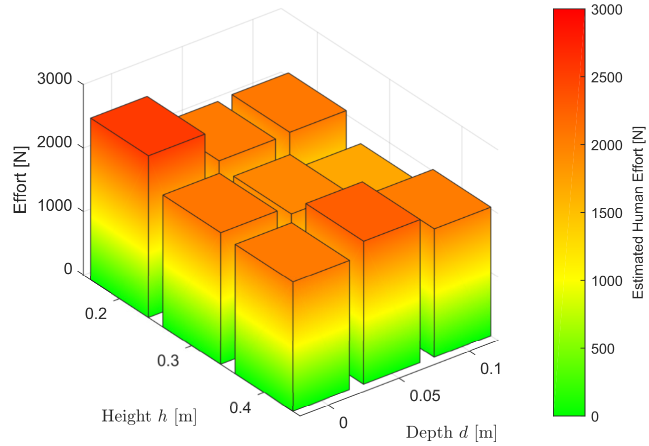

Fig. 6: Estimated human effort corresponding to a single subject. We consider that regions with less effort are more comfortable.

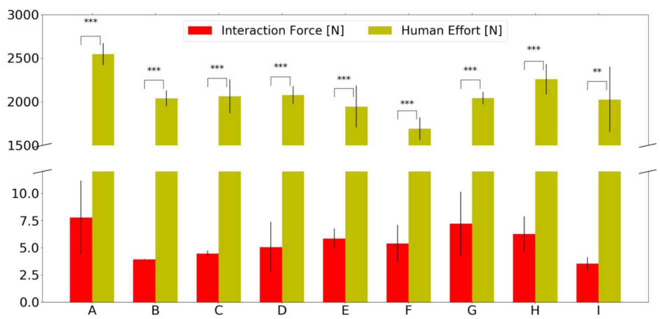

Fig. 7: Correlation between the human effort and the interaction forces corresponding to a single subject. The letters A to I correspond to the food delivery locations shown in Fig. 5.

To investigate the correlation with the estimated interaction forces between the human and the spoon (our previous work), we synchronized the data from the accelerometer mounted on subject and the accelerometer mounted on the spoon. We identified each biting occurrence from the experiments' video and the accelerometer data on the spoon. Then, we consider a period of time from 1 second before and to 1 second after each biting occurrence to estimate the human effort. This rough time window is useful for the purpose of the proposed estimation as in most biting occurrences such time is not exceeded and the human effort does not increase when the human is at rest.

From Fig. 6, we observe that the food-delivery location with the minimum human effort is at depth $d = 0.1$ m and height $h = 0.3$ m.

We analyzed the correlation between the data obtained from both accelerometers (*i.e.*, on the subject and on the spoon) to determine whether the acceleration data on the human torso is redundant with that from the one on the robot spoon and can, therefore, be neglected. The results are shown in Fig. 7. These results imply that the human effort estimated from the accelerometer on the human torso is not redundant, which suggests that the estimated human effort is a separate factor that contributes to the human comfort.

Moreover, we observe that both criteria, the interaction force and the human effort, coincide in that the least comfortable food-delivery location is A ($d = 0$ m and $h = 0.2$ m), the lowest and furthest from the subject. Location F requires the least effort to reach the spoon and go back to the neutral pose but it has an average interaction force. On the other hand, location I presents the lowest interaction force when retrieving the food from the spoon but it requires an average human effort to reach the spoon and go back to the neutral pose.

Finally, we extracted screenshots of the most and least comfortable regions for a subject to exemplify such cases, as well as a highly uncomfortable region (Figs. 8 to 9). As shown in Fig. 8, the user keeps a straight posture and the opening of his mouth is relatively small when eating in the most comfortable region. On the other hand, when eating in the least comfortable region, the subject crunches to reach the spoon and the opening of his mouth is relatively big, as shown in Fig. 9.

V. Conclusion

This paper proposed to quantitatively evaluate the comfort of food-delivery locations by estimating the human effort while eating with an assistive device. In particular, we investigate the influence of the food-delivery location in the comfort of a commercially-available eating assistive device. Rather than using an expensive, bulky force sensor, we use only the accelerometer to estimate the human effort during the feeding process.

We tested our concept with five healthy subjects and presented the results of the human effort estimation for multiple food-delivery locations. The experimental results show that quantitatively evaluating the comfort of an eating assistive device is feasible using an accelerometer.

The results suggest that the estimation of the human effort is contribution factor to the human comfort as it presented significant differences with the estimated interaction forces. Further experiments are needed to shed more light on this.

Future work includes further studying the effect of variable mass and different eating styles. Moreover, the presented quantitative evaluation should be complemented with a subjective evaluation, and the assumptions that higher interaction forces and higher human effort lead to less comfort should be further verified.

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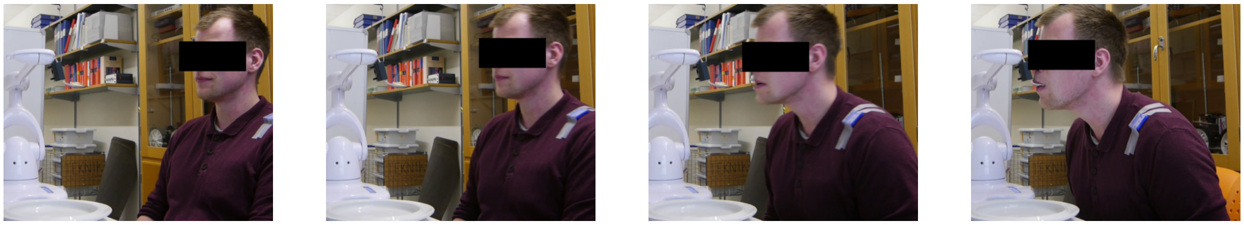
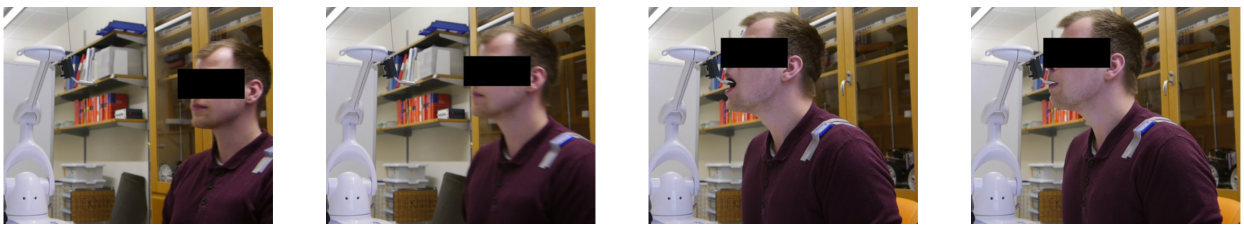


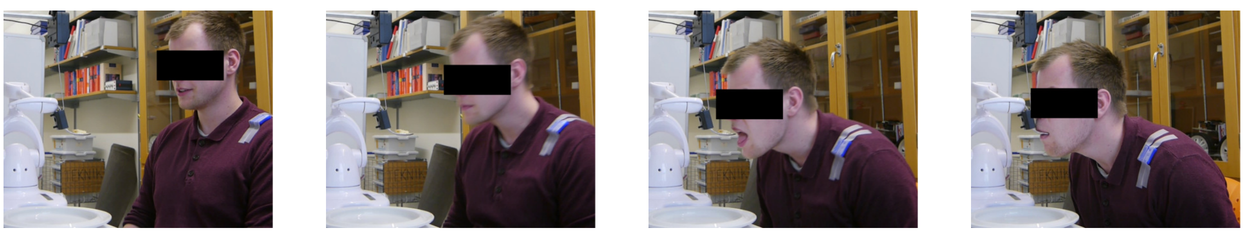
(a) $t = 0.0$ s (b) $t = 0.5$ s (c) $t = 1.0$ s (d) $t = 1.5$ s

Fig. 8: Example of the most comfortable region for food delivery according to the human effort criterion. The subject keeps a straight posture and opens his mouth in a natural way when approaching the spoon to retrieve the food. This example corresponds to the food-delivery location depth $d = 0.1$ m and height $h = 0.3$ m.



(a) $t = 0.0$ s (b) $t = 0.5$ s (c) $t = 1.0$ s (d) $t = 1.5$ s

Fig. 9: Example of the most comfortable region for food delivery according to the interaction force criterion. The subject has to stretch to reach the spoon and has to widely open his mouth to retrieve the food from the spoon. This example corresponds to the food-delivery location depth $d = 0.1$ m and height $h = 0.4$ m.



(a) $t = 0.0$ s (b) $t = 0.5$ s (c) $t = 1.0$ s (d) $t = 1.5$ s

Fig. 10: Example of the least uncomfortable region for food delivery according to both criteria. The subject has to crunch to reach the spoon and has to widely open his mouth to retrieve the food from the spoon. This example corresponds to the food-delivery location depth $d = 0$ m and height $h = 0.2$ m.