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The development of a real-time wearable motion replication platform with spatial sensing and tactile feedback

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***Abstract*—The human body motion is a very important mean of expressing a person's emotion, knowledge and experience, as well as an effective communication tool in inter-personal interaction. We aim to provide a methodology for seamless integration of movements between the real human and the virtual one in Co-space, enabling motion replication in both directions. We developed the prototype systems consisting of a wearable InterfaceSuit that enables human motion replication and learning in Co-space, and a human-to-human motion replication methodology with multi-modal feedback mechanisms. We employed the wearable inertial sensors and optical linear encoder sensors to capture human body movement, and designed the haptic guidance device – 3 Dimensional Orientation Guide prototype with polyester tactor holder and elastic arm bands made of light-weight material for portability. We integrated sensing and feedback devices to build up a multi-resolution upper arm interfaceSuit to capture finger movements and arm movements (wrist, elbow and shoulder) and as well as wearable vibrotactile devices, sensor systems, and the control system for multimodal feedback.**

I. Introduction

Motor learning is the process of students improving the smoothness and accuracy of movements under instructions. Through motor learning the human is capable of achieving very skilled behavior, and through repetitive training a degree of automation can be expected. Human five senses - audition, smell, taste, touch, and vision - provide a variety of channels to give real-time feedback, and thus are of paramount importance to human interactions with each other, as well as with the environment. Comparing to auditory semantics feedback, although both of visual and touch feedbacks present more direct forms of spatial information of movement, the touch feedback is the most difficult for instructors to give students during the movement. Therefore, a spatial relationship through touch feedback between instructors and students needs to be explored in order to make use of tactile aid, the most effective way to assist human in motor learning by a spatial feedback that gives human a physical guidance in how to perform the series of movements.

5-DOF robotic suit designed by Massachusetts Institute of Technology chose the Vicon motion capture system through use of high speed IR cameras to find the five observed joints: wrist flexion/extension, wrist abduction/adduction, forearm rotation, elbow flextion/extension, and upper arm rotation [1]. Eight vibrotactile actuators were placed around each joint to allow proportional feedback along specific joint angles and projections. A tactile system designed by the U.S. Naval Aerospace Medical Research Laboratory for military pilots is the Tactile Situation Awareness System (TSAS) [2]. The TSAS is a vest filled with 32 tactors, which is worn on the torso of a pilot. The system communicates with the pilot via vibration signals to the skin of the torso, which are initiated by the vibrators in the vest. The system was designed in response to aircraft mishaps attributed to spatial disorientation which occurs when the pilot is unaware of his orientation in space and cannot decipher if the aircraft is reading down or up. The system was designed so that the location of the vibration on the torso directly relates to the position of the aircraft. For example, vibration applied to the front of the torso signals that a correction is needed for the front of the aircraft, and vibration applied to the left side of the torso signals that a correction is needed for the left side of the aircraft.

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In the paper, we present a tactile feedback device which effectively generates multiple directional instructions. With the knowledge of skin characteristics, the device, which aims to generate real-time corrective tactile feedback to the object's body to increase users' situational awareness and facilitate in motor learning, has been developed. In Fig. 1, both of master and student are wearing sensing devices to obtain own motion information. The motion information is send to a central processor and then compared for motion indicators to give instructions. Comparing to the MIT vibrotactile feedback suit, sensors are worn on body according to the kinematic model of human body and thus the device does not need external structures such as what were used in Vicon system. In addition, the tactile feedback can be used in training with no visual feedback. Those are more useful in training motion to the blind, furthermore, for outdoor activities or space limited application.

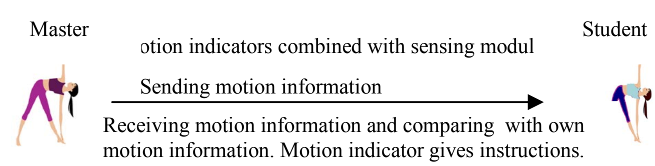


Fig.1 Illusion of Master-Student motor learning via tactile feedback devices

II. Procedure System Components and Model of Motion Comparison Systems

A. Human Kinematic Model

If the human frame is divided into its major segments or limbs connected by joints, then the resulting sketch is a gross model of the human frame. We can further simplify this model by representing the segments by ellipsoids and frustums of elliptical cones as in Fig. 2(a). For analysis purposes, it is convenient to number and label the human model segments. The relative lengths of human body segments in the model are ratios of lengths which can obtained from anthropomorphic measurement. The human frame modeling in Fig. 2 is sometimes called inertial segment modeling. The model itself is sometimes called a gross-motion simulator. We will use this model our analysis of human body kinematics and dynamics.

B. Motion Comparison between master frame and student frame

Once segments of a human frame are defined, motion differences between master's and student's segment with the same label can be represented by vector $\Delta\theta$. If one master's segment $R1_{master}$ and student's segment $R2_{student}$ are:

$$R1_{master} = \begin{bmatrix}\vec{x}_1 & \vec{y}_1 & \vec{z}_1\end{bmatrix}$$
$$R2_{student} = \begin{bmatrix}\vec{x}_2 & \vec{y}_2 & \vec{z}_2\end{bmatrix}$$

Then

$$\Delta\theta = \begin{bmatrix}\Delta\theta_x & \Delta\theta_y & \Delta\theta_z\end{bmatrix} \quad (1)$$

Where

$$\Delta\theta_x = \cos^{-1}\left(\frac{\vec{x}_1 \bullet \vec{x}_2}{|\vec{x}_1||\vec{x}_2|}\right)$$
$$\Delta\theta_y = \cos^{-1}\left(\frac{\vec{y}_1 \bullet \vec{y}_2}{|\vec{y}_1||\vec{y}_2|}\right) \quad (2)$$
$$\Delta\theta_z = \cos^{-1}\left(\frac{\vec{z}_1 \bullet \vec{z}_2}{|\vec{z}_1||\vec{z}_2|}\right)$$

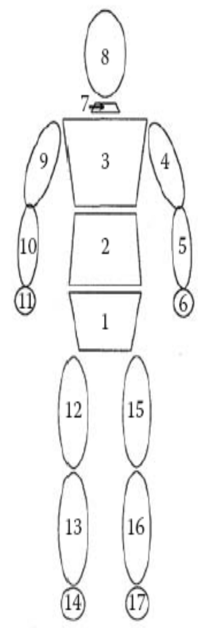
Therefore, the quantitative comparison is written as:

$$M_{segment} = \frac{\left[\sum_{i=x}^{z}\left(1 - \frac{\Delta\theta_i}{90}\right)\right]}{3} \quad (3)$$

where $M_{segment}$ is the mean of three variables.

C. System Components of Motion Capturing System

The system components include a device that employs small state-of-the-art inertial measurement units (IMUs), which are mounted on segments of the subject. The IMUs are commercially available InterSense sensors. Each IMU is a ''9-DOF'' solid state motion sensor, a miniature gyro-enhanced MARG (Magnetic, Angular Rate, Gravity) system that provides drift-free 3D orientation as well as calibrated 3-DOF linear accelerations (from 3-axis accelerometers), 3-DOF angular velocities (from 3-axis gyroscopes) and 3-DOF magnetic data (from 3-axis magnetometers). The sensors compensate for the drift errors from the integration of the angular velocity data, and have singularity free orientation. We developed the data capturing and processing programs to capture the orientation, acceleration and rotational velocity files from the sensors, and to process the orientation data into the parameters of pitch, yaw and roll and construct the real-time kinematic model. All data is transferred from the InterSense to the PC via 2.4GHz wireless channels, allowing the system to be run with any PC loaded with the development programs, allowing an increased level of portability ideal for on-field measurements. In order to measure the joint angles, we employ the 1-DOF Optical Linear Encoder (OLE) developed by Nanyang Technological University.



Segment Number	Segment Name
1	Pelvis or lower-torso body
2	Midriff or mid-torso body
3	Chest or upper-torso body
4	Left upper arm
5	Left lower arm
6	Left hand
7	Neck
8	Head
9	Right upper arm
10	Right lower arm
11	Right hand
12	Right upper leg or right thigh
13	Right lower leg
14	Right foot
15	Left upper leg or left thigh
16	Left lower leg
17	Left foot

(a) (b)

Fig. 2 Human Kinematic Model (a) Modeling the human frame by ellipsoids and elliptical cones (b) Numbering and labeling the human frame model

D. Validation of System Components

In order to assess the performance of motion capturing system, we conducted a variety of experiments for validation of OLE and inertial captured data [3]. The first set of tests was conducted to evaluate the accuracy of the OLE in ideal condition, with rigid joint and link, actuated by PowerCube. This PowerCube rotary module has a 2000 pulse per revolution encoder, which translates into 0.18° per pulse. Displacement results from the linear encoder were taken while the rotary module was rotated from 0° to 90° at intervals of 10°. The readouts from the linear encoder, converted to degree, were plotted against the Powercube rotation. Fig. 3

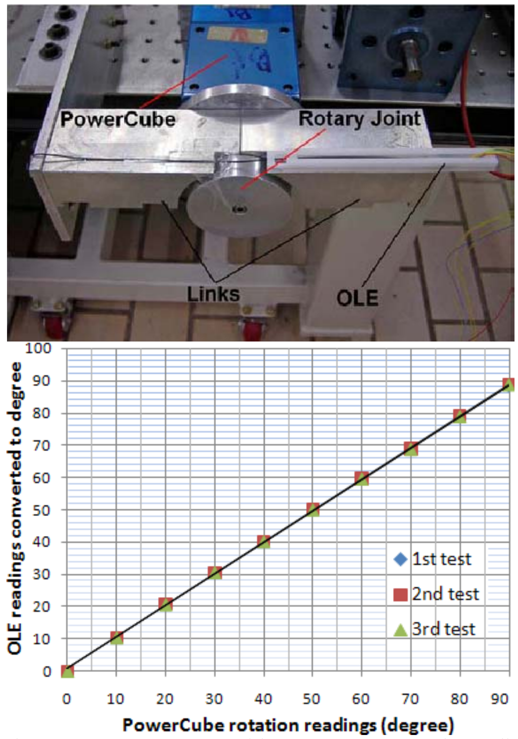


Fig. 3 OLE measurements with respect to PowerCube readings [6]

illustrates a linear relationship with a correlation coefficient of 0.99 and RMS error of 1.2 degree between the two systems. The second set of testing was made to evaluate the accuracy of inertial sensors. Each body segment with attached inertial sensor was tested individually with Motion Analysis system. The subject was first asked to wear the head sensor to run through a set of three trials involving range-of-motion tests comprised of roll, pitch and yaw motions. For each of the three trials the parameters of roll, pitch and yaw were output from the sensor, and calculated from the Motion Analysis marker data. The result was a roll average deviation of 2 degree, a pitch average deviation of 1.2 degree, and a yaw average deviation of 3.7 degree. These deviation values can be caused by many factors, such as the offset between the sensor coordinate frame and the Motion Analysis coordinate frame, the differences of algorithm accuracy, and calculation deviations.

III. System Components and Model of Vibrotactile Feedback Systems

A. System Components

The system components include microcontrollers that receive the feedback instructions and then convert the instructions into analog signals, tactors that are derived by the analog signals to generate various vibrations strength in order to provide the tactile feedbacks for attached things and a wireless communication module for receiving wireless instructions [4]. As for tactile feedback information, the choice of tactors will critically impact the performances of tactile feedback systems, which can be proved by result reports of many experiments on human skins. We choose a flat type vibration motor which has the advantage of small size, light weight, little power consumption, and the ability of providing adequate vibrating strength that are distinguishable to human skins. Applied with the standard operating voltage as low as 5V, the tactor is able to generate 1g (9.8m/s2) vibration strength. This vibration level is above the discrimination threshold at forearm, which is about 0.6g. Tactors with this vibration strength are widely used in vibration devices which provide tactile stimuli to skin. Although the tactors frequency and amplitude cannot be independently controlled, they are simple to control and can provide perceptible vibration to skin. Except for the physical characteristics of tactors, furthermore, we need to concern the placements of tactors on human body, the adjustment of vibration strength, electrical and mechanical response time, and brain response time, when we convert kinematic information into tactile signals.

1) *How to place tactors*: The placement of factor describes the unique position of the tactors on the arm [7]. It can be positioned with a vector in the body frame, if its origin is assumed to be located at the intersection point of the longitudinal axis of the forearm and the cross section of the elbow.

2) *How to determinate vibrating strength with motion comparison results*: This factor describes the vibration strength of tactors, which is proportional to the voltage applied on tactors. The voltage is generated by digital and analog converter controlled by Pulse Width Modulation from microcontroller. Tactors are placed vertically with respect to the skin so that tactors exert a normal force on the skin during vibration.

3) *How to reduce response time*: This factor describes the period of time between the time when the student receives feedback instructions and the time when the student makes a correct movement. Much shorter the response time, more quick the student will make a rectification of the movement.

4) *How to design ergonomic mechanical and electrical parts*: Considering power consumption and the ability of providing sufficient information of 3 DOF motions according to the human kinematic model, the minimum number of tactors to make up guidance for one body segment is three. More than three tactors will cover larger segmental area, and also may result in a complicated and bulky device. Since we employ tactors to indicate different spatial positions, for example, three tactors for pitch, yaw and roll respectively, and there are many ways to place tactors, we need to fix the placement of the tactors in order to generate consistent instructions to avoid the perception differences among human bodies. Therefore,

based on the three tactor design, three spatial configurations to assemble the orientation guide were studied. The first configuration is to arrange the tactors in a triangular shape. The second configuration is a bracelet shape. The third configuration is a right-triangular shape. Furthermore, we calculate relative positions among three tactors and then make mechanical design through adjustment of tactors distances. For instance, the length of the segment like forearm is denoted by LA, width of the segment near the reference point like wrist denoted by W, and thickness of the forearm near the wrist denoted by T, the values of each tactors location vector can be written as the followings:

- *Triangular Shaped Arrangement*

The distances between two tactors *x*2 and *x*3 are:

$$|P_1P_2| = \sqrt{(LA - x_2)^2 + \left(\frac{W}{2}\right)^2}$$
$$|P_1P_3| = \sqrt{(LA - x_3)^2 + \left(\frac{W}{2}\right)^2} \qquad (4)$$
$$|P_2P_3| = W$$

- *Bracelet Shaped Arrangement*

The distances between two tactors *x*2 and *x*3 are:

$$|P_1P_2| = \sqrt{(LA - x_2)^2 + \left(\frac{W}{2}\right)^2 + T^2}$$
$$|P_1P_3| = \sqrt{(LA - x_3)^2 + \left(\frac{W}{2}\right)^2 + T^2} \qquad (5)$$
$$|P_2P_3| = W$$

- *Right-Triangular Shaped Arrangement*

The distances between two tactors *x*2 and *x*3 are:

$$|P_1P_2| = LA - x_2$$
$$|P_1P_3| = \sqrt{(LA - x_3)^2 + \left(\frac{W}{2}\right)^2 + \left(\frac{T}{2}\right)^2} \qquad (6)$$
$$|P_2P_3| = \sqrt{\left(\frac{W}{2}\right)^2 + \left(\frac{T}{2}\right)^2}$$

Since we want users to distinguish vibration between the adjacent tactors, we must decide minimum distances between two-point limen. I t can be seen that *Right-Triangular Shaped Arrangement* has to cover the largest body area while *Bracelet Shaped Arrangement* covers the smallest body area.

B. System Model of Feedback Instruction Generation

1) Vibration Control of Individual Tactor: To simplify the vibration control, here, we only consider two kinds of vibrations: constant vibration and linear vibration.

- *Constant vibrating strength*

It is quite straightforward to generate the constant vibration strength, since we only need to provide invariable voltage through pulse width modulation in a period of time. We also can generate different instructions when we take different voltages with time evolution. When the vibration is following on-off pattern, it can be called "burst" vibration. The advantage of this type of control is its simplification, however, sometimes it is difficult to decide which value of period of time is optimal and this value will lead to undesirable response delay.

- *Linear vibrating strength of tactors*

Following time revolution, we can linearly increase or decrease the vibration strength through linearly adjusting the input voltages. The advantage if that we do not need to concern the period of time as what in constant vibration. The remaining issue is that we still need to adjust a linear coefficient.

2) Vibration Mode: There are several modes to make use of three tactors together, coupled with different individual tactor functions.

- *Synchronous Mode 1*

This mode is coupled with Triangular Shaped Arrangement. Each tactor provides constant vibrating strength throughout the entire time interval. The vibration strength for each single-axial forearm motion is distinguished by providing different Pulse Width for three tactors. It means that a net force, which is proportional to the orientation difference measured in each cycle, is created at the proper point to generate an intuitive tactile feedback to direct the subject's body segment motion accordingly.

- *Synchronous Mode 2*

This mode is coupled with Bracelet Shaped Arrangement. The time of each cycle is divided into three time intervals. Each tactor provides constant vibrating strength at the time interval, but different ones among time intervals. By this means a net force together with a directional clue are created to render the subject's segment motion intuitively. If the subject is required a multiple DOF movement, three tactors will provide one type of vibration indications for one DOF, and then another one for a next DOF. That is to say, the three tactors are provides indications for the multiple DOFs in a sequential order.

- *Asynchronous Mode*

This mode is coupled with Right-Triangular Shaped Arrangement. Each tactor provides a linear vibrating strength at the time interval and provides indications for one DOF motion independently. That is to say, for a specified DOF motion, only the corresponding tactor is activated. When the movement is in the positive direction, the vibration strength is enhanced; otherwise, the strength is weakened. The vibrating strength in each cycle is proportional to the orientation difference. In the event of multiple DOF motions, the three tactors can show the respective vibration statuses simultaneously with their own calculated strengths.

3) Other physiological concerns: When leveraging multiple tactors for multiple DoFs on a body, we need to discuss human physiological factors of responses to instructions provided by tactors.

- *Response mechanism*

The lifecycle of feedback includes the time that the tactors generate instructions through vibration strengths and the time that humans process instructions they received. Firstly, it takes time to complete one vibration mode. Sometimes a vibration mode is quite time-consuming. Secondly, human will give correct response only after a few rounds of trials; in particular, this case often happens in multiple DOF feedback.

- *Vibration designs in each mode*

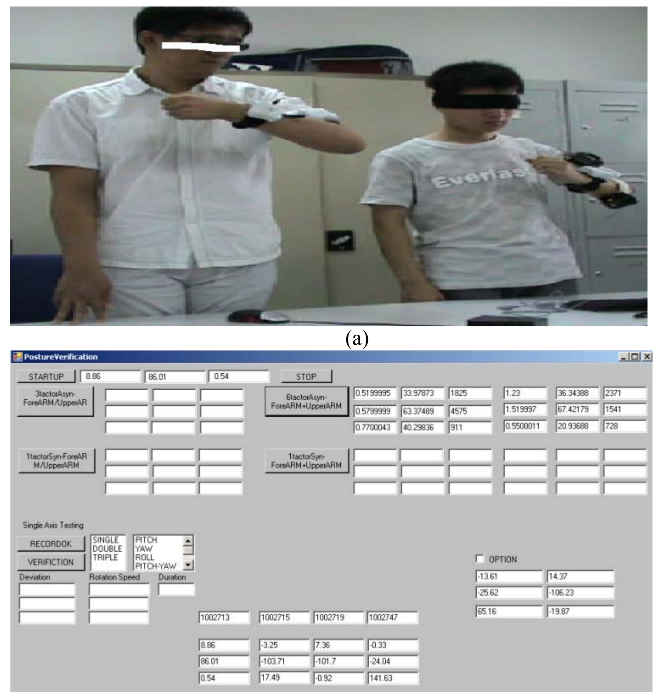
One the one hand, as for single-axial segment motions, synchronous mode need to make use of three tactors together. In other words, three tactors are coupled together for single DOF motions. In order to provide one instruction, one tactor's vibration status depends on the other two. This leads those users to pay attention to tactors together, making it difficult in perceive indications. Asynchronous mode uses one tactor to indicate direction of one local axis and so three tactors are working independently. The perception of instruction will be simplified. On the other hand, as for multiple-axial segment motions, synchronous mode No.1 works with the principle of superposition. Although the combined pattern is different from any of the six basic modes, the new pattern does not provide any intuitive or clear instruction to the user and is difficult to guide the user in adjusting postures. Synchronous mode No.2 is based on with a sequential principle. Users can only access the information for a single-axial motion at one time. This design increases response time overhead. In summary, among three modes, the *Right-Triangular Shaped Arrangement* with *asynchronous mode* will provide best indications for human body perception.

IV. Experimental Procedure

We designed three sets of experiments to examine the performance of vibrotactile when they are mounted on body. Here, we take the arm as the example to explore the design space, because the arm has multiple DOFs and also is convenient for us to examine the optimal choice of tactors, for instance, the minimal number of tactors of obtaining desired responses to instructions. Table 1 indicates that the first two experiments are focused on the characterizing the response of human with three tactors on 3 DOFs forearm and upperarm, respectively. The rest of experiments explored the designs simplified with 6 DOFs arm.

TABLE I The experiment settings for multiple DOFs of arm

No.	Degree of Freedoms	Placement of Body	No. Tactors	No. Tactile Device
1	3	Forearm	3	1
2	3	Upper arm	3	1
3	6	ForEarm+Upper arm	6	2



(a)

(b)

Fig. 4 Experiment setup, with one master wearing measurement sensors and one student wearing measurement sensors and tactile devices. (a) Hardware settings (b) Developed software

- *Human Subjects*

The subjects were recruited from the population of 18- to 30-year-old students at the University. They were in good health in skin perception without any medical condition that could affect tactile sensitivity.

- *Body Sites*

Figure 4 shows the most complicated configurations of placement of sensors and tactile. As for both of masters and students, the motion sensors were placed on forearm, elbow and upper arm, respectively. In addition, the vibrotactiles were placed on both of forearm and upper arm. To copy with different experimental settings, the sensors and tactiles can be removed or kept to meet the testing requirements. For example, the experiment No.1 treats the forearm, and thus we could directly put the sensors and tactile on student's forearm. The experiment No.2 examines students' upper arm response to instructions produced by three tactors. We can put back sensors and tactile on students upperarm and remove those on forearm. Without changing hardware settings, we can enable individual tactor to vibrate and/or disable the others for different vibration mode. Therefore, the configuration of sensors and tactile devices are quite dynamics.

- *General Procedures*

The studies were done in a convenient room. In order to make sure that each tester has understood operations of tactors, we let one tactor vibrate with a constant PWM as well as the adjacent tactor vibrate with half of this. If participants claim that they can distinguish the two vibrations, then we confirm that the tester has known the purpose of the testing and can differentiate feedback instructions. Furthermore, in order to make testers understand the movement around pitch, yaw and roll, testers were asked to perform serials of movement with the help from the tactile instructions. The tasks were: rotating the forearm left and right around yaw-axis, rotating the forearm up and down around pitch-axis, and then rotating forearm around roll-axis. After few rounds of tries, if the testers can do correct movement, then we confirm that the basic requirements of the three experiments are satisfied. The three experiments were conducted one by one, and we monitored the whole process and collected the results. As for all experiments, two persons need to be involved, in which one person is called master and the other is called student. The student cannot see the masters' posture and only can search for masters' the forearm and upper arms postures with the tactile instructions.

- *Results and Discussion*

For all of three experiment settings: forearm, upper arm and both of forearm and upper arm, according to testing results shown in Table II, the students could find out masters spatial positions through tactile spatial instructions. The mean of searching times of whole arm, upper arm, and forearm are 40s, 6s and 8s, respectively. The search time of whole arm does not equal to the sum of those of forearm and upper arm. We think that this may be caused by testing procedures, because we observed that students were often confused with six tactors and as well as the upper arm and forearm so that they cannot make correct decision on which axis they should follow in order to adjust postures. We also observed that the processing time on different axes are also not the same. The cost of timing on roll is much larger than those on pitch and yaw. We still need to conduct more in-depth investigation and also simplify the testing procedures on further.

V. CONCLUSION

It is clear that instructions through vibrotactile can provide feedback information to guide testers towards desired positions through adjustable vibration strength and positions. The developed system can support both of real-time posture capture and generation of feedback information. Nevertheless, the human processing time to upper arm, forearm and whole arm is not evenly distributed; and also are beyond our toleration. Therefore, in-depth investigations of tactile optimization are required to conduct on the reduction of response time.

TABLE II THE EXPERIMENT RESULTS FOR MULTIPLE DOFS OF ARM

No. Experiment			Mean of Deviation	Mean of Angle Speed	Mean of Response Time (ms)
1	FOREARM	PITCH	5.27	2.527	5906
		YAW	5.4	8.29	5000
		ROLL	16.35	0.25	12750
2	UPPER ARM	PITCH	5.71	2.21	5718
		YAW	5.52	6.37	3594
		ROLL	1.55	0.65	9437
3	FOREARM	PITCH	0.52	33.99	18250
		YAW	0.58	63.38	45750
		ROLL	911	40.30	9110
	UPPER ARM	PITCH	0.55	36.34	15410
		YAW	1.23	20.93	7280
		ROLL	1.52	67.42	23710

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