The RT-Chair: a Novel Motion Simulator to Measure Vestibular Perception

Luigi F. Cuturi*[1], Diego Torazza[2], Claudio Campus[1], Andrea Merello[3], Claudio Lorini[3], Marco Crepaldi[3], Giulio Sandini[2], Monica Gori[1]

***Abstract*— Vestibular perception is useful to maintain heading direction and successful spatial navigation. In this study, we present a novel equipment capable of delivering both rotational and translational movements, namely the RT-Chair. The system comprises two motors and it is controlled by the user via MATLAB. To validate the measurability of vestibular perception with the RT-chair, we ran a threshold measurement experiment with healthy participants. Our results show thresholds comparable to previous literature, thus confirming the validity of the system to measure vestibular perception.**

***Clinical relevance*— This research presents a novel motion simulator to deliver combined or independent stimulation of the vestibular canals and otolith organs.**

I. INTRODUCTION

Vestibular sensory information is fundamental to perceive self-motion properties such as changes in velocity, heading direction [1], [2] and disambiguation of visual object motion from self-motion [3]. The peripheral vestibular system is composed by the semicircular canals, sensing angular acceleration and the otolith organs sensing linear acceleration. Much research has employed technological solutions to deliver self-motion stimulation to assess vestibular functionality and perception. To measure the two components of the vestibular system, motion systems used for scientific and clinical purposes have been developed to deliver rotations or translations. In the first case, the most common system is the Barany or rotatory chair, a motorized chair capable of delivering 360 endless rotation (e.g.[4], [5]). In the case of translation, motorized sleds are used to deliver linear translations either on the inter-aural (IA), that is to the left or right, and the naso-occipital (NO) axis, that is forward or backward (e.g. [6]). A combination of rotatory and linear movements can be achieved with more complex systems that allow 6 Degrees Of Freedom (DOF) (e.g. the MOOG 6DOF2000E, for driving simulation [7] and vestibular research [8]), or more (e.g. the MPI motion simulator [9]). These systems are often expensive and need large operative space. In this work, we present a newly developed technological solution to deliver both linear and rotational self-motion stimuli to study and test vestibular perception in humans, which is the Rotational-Translational Chair (RT-Chair). The RT-Chair (see Fig. 1) is a customizable motion apparatus which comprises a rotatory chair over a cart that allows earth-horizontal linear translation. The system is provided with two motors to deliver passive translations and rotations either independently or combined. Thus, the RT-Chair allows independent or combined stimulation of vestibular components such as the otolith organs and the semicircular canals. From a clinical perspective, the RT-Chair would allow the clinician to disambiguate between the two vestibular components' dysfunctionalities, thus representing an innovative instrument useful for diagnostic purposes. Material costs range between \$12K and \$14K. Additional equipment can also be integrated to deliver multisensory stimulation such as Virtual Reality (VR) head sets or binaural headphones. The RT-Chair can also be adapted to test children (e.g. by substituting the seat), thus extending its applicability to developmental research and clinical testing. In the work presented here, we aim to validate the RT-Chair by testing human participants with a self-motion threshold procedure for linear and rotational movements presented independently.

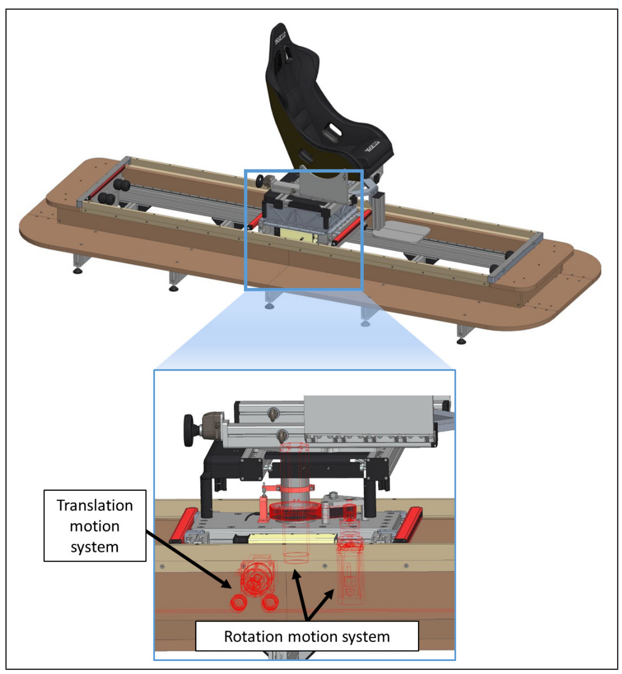

Fig. 1. Representation of the RT-Chair. The top panel shows the RT-Chair. In the lower panel, highlighted in red the two motors and the systems used to deliver movements are represented.

*luigi.cuturi@iit.it

[1]Unit for Visually Impaired People, Istituto Italiano di Tecnologia, Via Enrico Melen 83, 16152, Genoa, Italy

[2]Robotics Brain and Cognitive Science Unit, Istituto Italiano di Tecnologia, Via Enrico Melen 83, 16152, Genoa, Italy

[3]Electronic Design Laboratory, Istituto Italiano di Tecnologia, Via Enrico Melen 83, 16152, Genoa, Italy

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II. DESCRIPTION OF THE RT-CHAIR

A. Mechanical Components

The RT-Chair is a serial 2DOF mechanism designed to fulfill vestibular stimulation specifications. One of the main requirements is a smooth and vibration-free motion, with no backlash and least possible motion-related noise perceived by the subject. Maximum speed required is 0.3 m/s for translation and 1.75 rad/s for rotation; maximum acceleration required is 5 m/s^2 for translation and 1.75 rad/s^2 for rotation. The resolution requirement is 1 mm for translation and 4e-03 rad for rotation. The base structure is composed of commercial aluminum alloy profiles, covered with a safe and comfortable wooden platform to allow easy step up and down for the subject. The RT-Chair lays on ten rubber foot, with adjustable height to guarantee the best stability. Foots can be raised to lay down the device on 4 pivoting wheels: in this way the device can be easily moved by a single person without any lifting tool. To achieve maximum smoothness the translation trolley is equipped with four recirculating balls sliders (THK HSV20CSS) running on hardened steel rails (THK HSV20-2600L-E30). The translation is driven by a brushless motor (Elmo Mecapion APM-SC05ADK-9, see Fig. 1) through a low backlash single-stage planetary reduction gearbox with a 10:1 ratio (Shimpo VRL-070B-10-K5-19DC16). Rotational motion is converted to linear by a T5 timing belt. The motor is located on the trolley (see Fig. 1). The translational range is 1965 mm and there are rubber bumpers on each side to absorb kinetic energy in case of an emergency (e.g. the chair-trolley hits the end of the rail), avoiding any damage to the subject and the structure itself. On the trolley there is also the second brushless motor (Elmo Mecapion APM-SC03ADK-9), that drives the rotation trough a two stage reduction. First stage is a low backlash single stage planetary reduction gearbox with 10:1 ratio (Shimpo VRL VRL-050B-10_K5-14BK14); second stage is a 4:1 T5 belt, with 20T pinion and 80T spur. Total reduction is 40:1. The rotation is 360 degrees endless: the shaft is hollow and accommodate a rotational electrical contact to reach the seat with signal/power cables if needed. The output of rotation mechanism is directly on the shaft that holds the chair frame. The aim of the device is to generate a precise motion path on the head of the subject. To this end, Finite Element Method (FEM) analysis has been carefully carried out to withstand dynamic loads with minimum elastic deformation. Based on this analysis, we designed the shaft (supported on dual deep groove ball bearings), and all chair frame to reduce any potential deformation of the frame that would lead to a discrepancy between desired trajectory and the real one to a negligible amount.

The seat is a racing cars composite shell seat (Sparco® EVO III), with four point motorsport belt, for the best comfort and fastening of the subject to the system. The seat frame is composed of a hybrid structure of commercial aluminum alloy profiles and custom CNC plates and embeds several seat adjustments. The seat pitch tilt can be continuously adjusted by two screws to reach the most comfortable position, and a planar X-Y system guarantees a total stroke of 265 mm in each direction to precisely adjust the head of the subject in the desired position respect to the rotation axis of the system. Two hand wheels are available to perform this adjustment with a display that shows the absolute position for each direction: subject's head position is easy to adjust and recorded for future reference and repeatability. For safety reasons the whole actuating system is completely protected with plastic 3D printed covers and there is an all-round footplate for the subject, both for comfortable foot and leg positioning during use and for safety during motion and ride up and step down.

B. RT-Chair Architecture

The two RT-Chair motors are controlled independently, using a nested control algorithm, that can accept sparse position point (X in the diagram, where X can be linear position or angle) to generate trajectories for the three loops, position P, velocity S and current I control (see top left corner of Fig. 2). The user, from a general purpose Personal Computer (PC) provides sparse position set-points to the Ethernet Motor Supervisor controller board (EMS) from an Ethernet connection. The EMS module generates the remainder position points using a minimum jerk algorithm, that follows the law:

$$X_p(t) = X_0 + S_0 t + \left[10(X - X_0) - 6S_0\right] t^3 + \\ \left[-15(X - X_0) + 8S_0\right] t^4 + \left[6(X - X_0) - 3S_0\right] t^5 \qquad (1)$$

where, $X_p(t)$ is the generated trajectory, t is time (updated on the desired rate basis), X is the final (target) position, X_0 is the initial position and S_0 is the initial speed (usually zero). Before transmittal to the Field-Oriented motor Controller (FOC) modules, these trajectory points are processed by the position controller, which runs on the EMS module (see diagram in Fig. 2). The FOC acquires the continuous speed

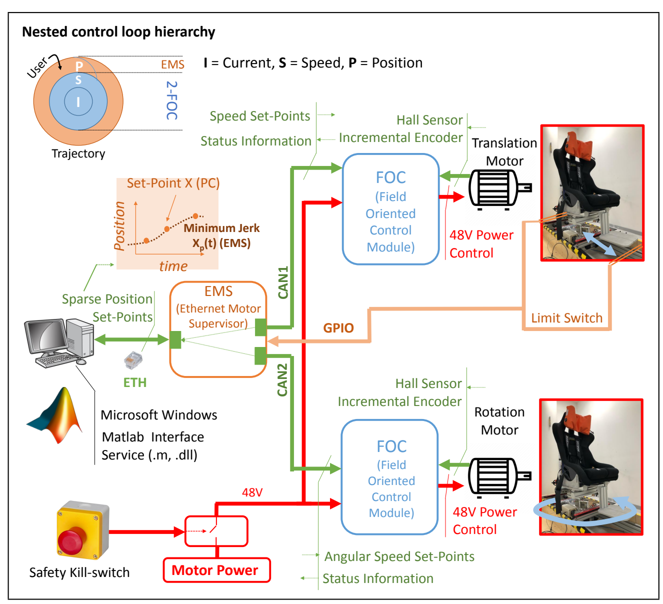

Fig. 2. Block scheme of the complete RT-Chair electronic control subsystem.

set-point stream (both for angular and linear actuators) calculated by the EMS module from two separate and independent Controller Area Network (CAN) buses, with a typical sample rate of ∼1 kHz, that can be configurable at user-level. In turn, the FOC modules implement the remainder loops based first on a Proportional-Derivative-Integrative (PID) controller on velocity, and a Proportional-Integrative (PI) controller on current. The motor power voltage is 48 V and provided from a dedicated cabinet, that can be immediately deactivated for safety reasons using a kill-switch, installed next to the PC station. The linear actuation stage comprises two limit switches that are used to establish the translation bounds for safety and avoid that the chair crashes on the mechanical limits. These, are connected to dedicated GPIO of the EMS module. We have used two position detectors on each motor, i.e., hall sensor and incremental encoder (redundancy), to increase the safety level of the machine. Each motor has a dedicated wiring to the corresponding FOC module. Each FOC provides control status information to the EMS module, that can be read on the PC for debug (real-time position, both rotation and translation with error flags).

To enable ease of use and successful integration in the environment normally used for cognitive experiments, we have implemented a Matlab™interface to the EMS module running on Microsoft Windows™. The software comprises a service that reads data from the Ethernet PHY, buffers it, and sends it to a named pipe of the operating system. At this point, a specific Matlab Dynamic Link Library (DLL) receives the data, runs depacketizing and provides information to the Matlab wrapper files (M-files) for user-level programming.

III. VESTIBULAR THRESHOLD MEASUREMENT

To test the functionality and the validity of the RT-Chair of measuring vestibular perception, we asked 7 healthy participants (age mean±SD = 29.3±3.1; 4 females; all right-handed) to perform a two-alternative forced choice self-motion direction discrimination task. Such task has been proven to be appropriate in the measurement of vestibular threshold as much as a detection task and is less influenced by potential vibrations of the motion system itself [10]. Participants were seated on the padded racing seat of the RT-Chair and their head was positioned against a vacuum pillow shaped according to the head with their forehead held with a padded strap to the chair. Four point motorsport seat belts were fastened around participants' upper body. Experiments were conducted in a darkened room. Prior to the experiment, the chair position was adjusted to align the head with the axis of rotation by means of an optical tracking system (Four Optitrack FLEX 3 100 FPS cameras with Motive software): chair position was adjusted until only in-axis rotations were observed. During stimulus presentation, sounds from the RT-Chair were masked by playing white noise in wireless headphones worn by subjects. Before each movement, a brief low-pitch tone provided the "GO" signal and the participant triggered the motion stimulus via button press. In the translation conditions only, right after the response was collected the participant was brought back to the start position at half velocity of the just presented stimulus. To avoid any potential aftereffects between two consecutive movements [11], a no motion time window of at least 3 s was assured between movements. Participants were blindfolded by means of swimming goggles occluded with black tape and positioned over a blindfold that covered their eyes. This procedure is in line with the cautions taken with most motion systems in use [11], [12], [13].The experimental procedures involving human subjects were approved by the local health service, Comitato Etico, ASL 3, Genoa, Italy.

We tested 3 movement conditions in separate blocks of trials: IA translation, rotation and NO translation. On each trial, participants experienced a 1 s physical-only passive motion stimulus and indicated the experienced movement's direction by using a wireless numeric keypad. For the IA translation and rotation conditions, participants indicated whether the movement was to the right or left; in the NO translation, participants indicated whether the movement was forward or backward. In each condition, we tested a total of 120 trials which began with 6 training trials with fixed movement magnitude. For the remaining trials, movement magnitude was determined by the Psi adaptive procedure [14] implemented using the PAL_AMPM routine from the Palamedes toolbox [15]. This procedure uses a Bayesian criterion to minimize the uncertainty associated with the parameter estimates of the psychometric function (i.e. mean and slope of the cumulative Gaussian fit). For each participant and condition, we then fitted a cumulative Gaussian to the data using the PAL_PFML_Fit routine from the Palamedes toolbox [15] which finds the best fit in a maximum likelihood sense (Guess and lapse rate were fixed at 0.02). The mean provides a measure of the movement perceived as "zero motion" which we refer to as the point of subjective equality (PSE) (see Fig. 3). We take the standard deviation of the distribution as a measurement of vestibular threshold (see Fig. 3), namely the just noticeable difference (JND) in movement magnitude between two above-threshold stimuli. For each subject, we obtained a total of three PSE and JND values, one for each type of movement.

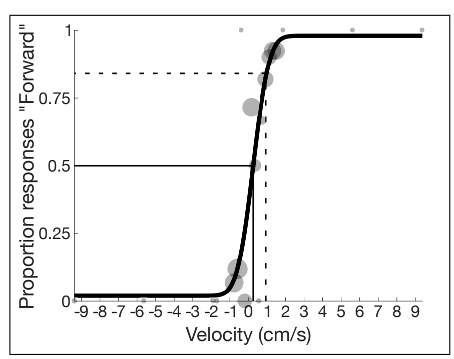

Fig. 3. Psychometric Fit. Performance of one representative participant in the NO translation condition. The solid vertical line corresponds to the PSE (0.26 cm/s). Dotted vertical line represents the PSE + JND (0.67 cm/s). The size of the dots is proportional to the number of repetitions for each stimulus value. Negative values indicate backward movement and positive values indicate forward movements.

The psychometric fit for an individual subject is reported in Fig. 3. JND and PSE values averaged across subjects for the three conditions are reported in Fig. 4. Normality of the data was confirmed with a Shapiro-Wilk normality test. One sample t-tests show the absence of directional biases in the PSE for all conditions (Translation IA: t = -1.22, p = 0.26; Translation NO: t = -0.89, p = 0.40; Rotation: t = -0.15, p = 0.88). Comparison of JND for IA VS. NO translations show no difference (pairwise t-test, p = 0.55) as previously observed in the literature [16].

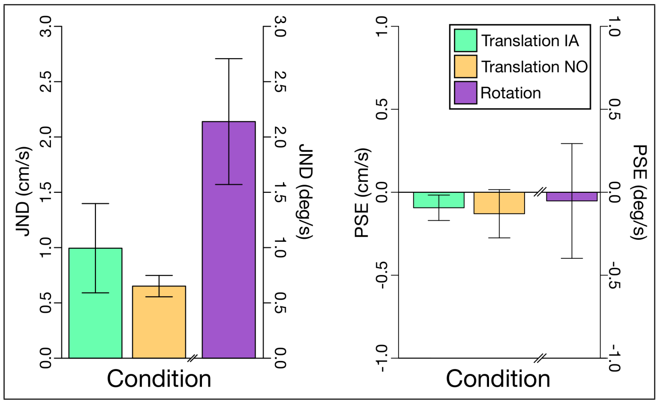

Fig. 4. Vestibular thresholds results. Mean of the JND (left panel) and the PSE (right panel) across participants for each movement condition are represented. Error bars indicate standard error.

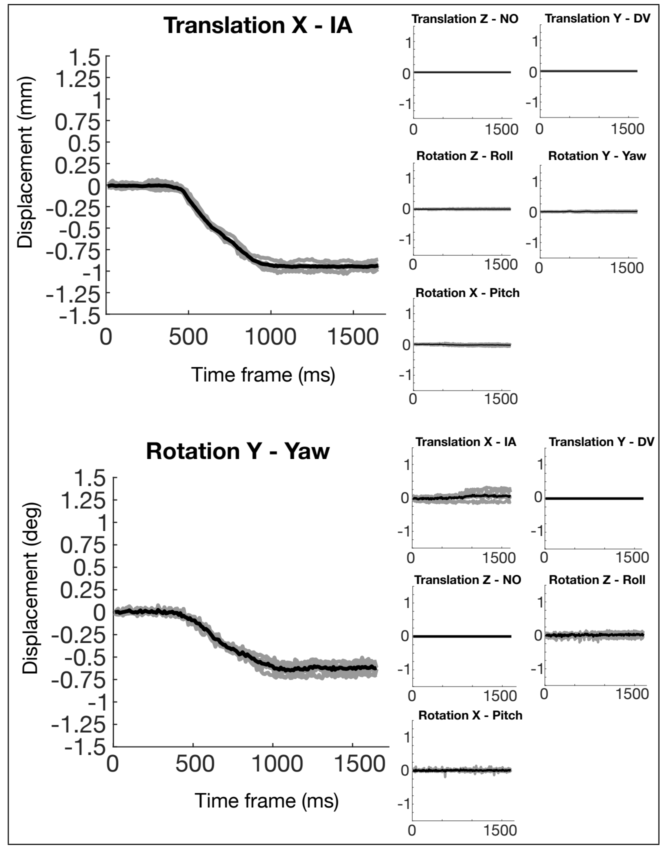

Fig. 5. Head motion tracking. Motion traces were recorded with an optical tracking system (Four Optitrack FLEX 3 100 FPS cameras with Motive software). The top panel shows the head displacement for 6 repetitions of a 1 mm IA Translation. The lower panel shows head displacement for 7 repetitions of a 0.6 deg rotation. Gray lines represent head movement at each repetition, black lines the average across repetitions. NO Translation traces resemble IA Translation traces and are not displayed to avoid redundancy.

IV. DISCUSSION

In the literature, vestibular thresholds have been measured to provide an understanding of healthy vestibular functionality. These findings provide a reference for clinical purposes in case of vestibular dysfunction. Our aim here is to validate the RT-Chair by comparing vestibular thresholds with previous works that recorded vestibular perception in vestibular loss patients and healthy subjects. Firstly, we observe that vestibular thresholds for the 3 tested movement conditions are lower than the vestibular thresholds measured in vestibular loss patients (see Table I). This result supports the RT-Chair as an instrument capable of measuring vestibular thresholds. Regarding healthy participants, although thresholds measured with the RT-Chair for IA translations and rotations are higher compared to previous literature, they tend to follow within 2 standard deviations from the mean of the values reported by [10] and [16]. Nevertheless, the observed differences might be due to methodological differences arising from: the properties of the motion profile (e.g. minimum jerk displacement profile VS sinusoidal acceleration profile), the methodology used to measure the threshold (Psi adaptive VS staircase procedure) and finally potential vibration induced noise in the RT-Chair compared to other motion systems in use. To overcome these potential limitations, future improvements in the RT-Chair will be pursued by comparing performance with different motion profiles and different threshold measurement procedures. Although motion tracking of participants' head during movement seem to report negligible additional vibrations (see Fig.5), mechanical changes will be pursued to improve stability and reduce potential unwanted vibrations. Nonetheless, given the comparison with patients' threshold, we firmly consider the RT-Chair an optimal candidate to measure vestibular perception both for research and clinical purpose. Moreover, in support of this finding, we do not observe significant directional bias in the PSE thus proving that movement's directions simulated with the RT-Chair are physically and perceptually unbalanced. This result indicates that the system is suitable to perform vestibular perception oriented research and clinical evaluation.

As known from the literature [18], vestibular thresholds depend on the frequency of movement, with increasing threshold level as the frequency decreases. Although in this work we focused on movements of 1Hz, the RT-Chair has been built to deliver movements of lower and greater frequency than 1 Hz, thus it provides the means to investigate also these aspects of vestibular perception.

In comparison to existent motion simulator devices, the RT-Chair has several advantages. The 2DOF system provides a unique combination of rotational and translational movements in the same device. Although devices used for research purposes sometimes overcome this limitation by reaching 6DOF (or more), rarely these devices are capable of

TABLE I

COMPARISON THRESHOLD TABLE. T STANDS FOR TRANSLATION. NUMBERS WITHIN PARENTHESES INDICATE STANDARD DEVIATION. ASTERISK INDICATES VESTIBULAR LOSS PATIENTS.

Study	Rot. deg/s	T-IA cm/s	T-NO cm/s
RT-Chair	2.13(1.50)	0.99(1.06)	0.65(0.25)
Chaudhuri et al.2013[10]	1.17(0.33)	0.55(0.19)	/
Valko et al.2012[12]	9.01*	4.45*	/
Valko et al.2012[12]	0.84	0.48	/
Roditi & Crane 2012[16]	0.9(0.7)	0.8(0.5)	0.9(1.0)
Karmali et al.2017[17]	1.06	0.61	/
Grabherr et al.2008[18]	0.64	/	/

delivering also endless 360 degrees rotations which instead is possible with the RT-Chair. Additionally, simultaneous rotational-translational stimulation is possible thus extending the use of the device to other applications such as the investigation and assessment of perceptual response to a curvilinear path. Considering that the thresholds presented in this work are greater than the minimum movement allowed by the device, below-threshold movements can be delivered; this aspect additionally confirms the validity of the RT-Chair to measure vestibular thresholds considering that direction of below-threshold movements cannot be detected. Moreover, below-threshold velocity levels can be potentially employed to position the participants without them being aware of the amount of the experienced displacement. For instance, studies on heading perception have been conducted with 6DOF motion platforms for the physical constraints of other motion devices [1], [2]. In the RT-Chair the below-threshold rotation of participants between trials would allow the experimenter to deliver heading stimulation of different eccentricity without the participant's awareness of the re-positioning. Altogether, these properties of the RT-Chair, makes this instrument an optimal candidate to pursue studies with VR headsets. The Matlab™interface allows the researcher to simply interlace visual and vestibular stimulation in order to match or mismatch VR and real-world simulated movements. Considering the range of movements that can be simulated, this combined stimulation could provide answers to open questions in the integration of visual and vestibular sensory cues such as the visuo-vestibular conflict that can give rise to cybersickness [19].

V. CONCLUSIONS

In the clinical field, the rotatory chair is the most used device to test vestibular functionality; however, this system elicits the response of semicircular canals only, leaving the otolith organs untested. With the RT-Chair presented here, we provide a novel motion simulator that can selectively stimulate the otolith organs or the semicircular canals by using one of the two motors. This aspect is fundamental in the case of clinical evaluation applications. The possibility of disambiguating between potential otolith and semicircular canals dysfunctionality allows the clinician to obtain a complete profile of the patient. Moreover, the combination of both movements simulated by the RT-Chair provides the means to test the interaction between the two vestibular components thus opening to novel potential assessment and rehabilitation procedures in basic and clinical research.

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