SUPPLEMENTARY MATERIAL

System Characterization

This section details the procedure used to identify the static friction and inertia of the motor and the passive mechanisms. For both the experiments, the low-level controller (ESCON 36/3 Maxon controller) was set in current control mode and the motor torque was proportional to the current across the coil; the proportionality constant was 0.9 Nm/A.

Static Friction Identification

The static friction for the passive mechanisms and motor-gearhead assembly was experimentally identified through the following procedure:

Step 1. Attach the mechanism whose static friction is to be measured to the actuator shaft; leave the shaft free to only measure the static friction in the motor-gearhead assembly.

Step 2. Initialize the number of repetitions to $n_r = 0$. N is the total number of repetitions to be carried out.

Step 3. Gradually increase the motor coil current (in steps of 0.1 A every sec) till the motor moves by 10deg. When the motor starts to move, set the motor current to 0 A for 2sec.

Step 4. If the motor has not reached its extreme position, then go to step 3. Else, check if $n_r = N$. If $n_r \neq N$, then increment n_r by 1 and go to step 5. Else go to step 6.

Step 5. Go to step 2 and apply the current steps in the opposite direction.

Step 6. Stop.

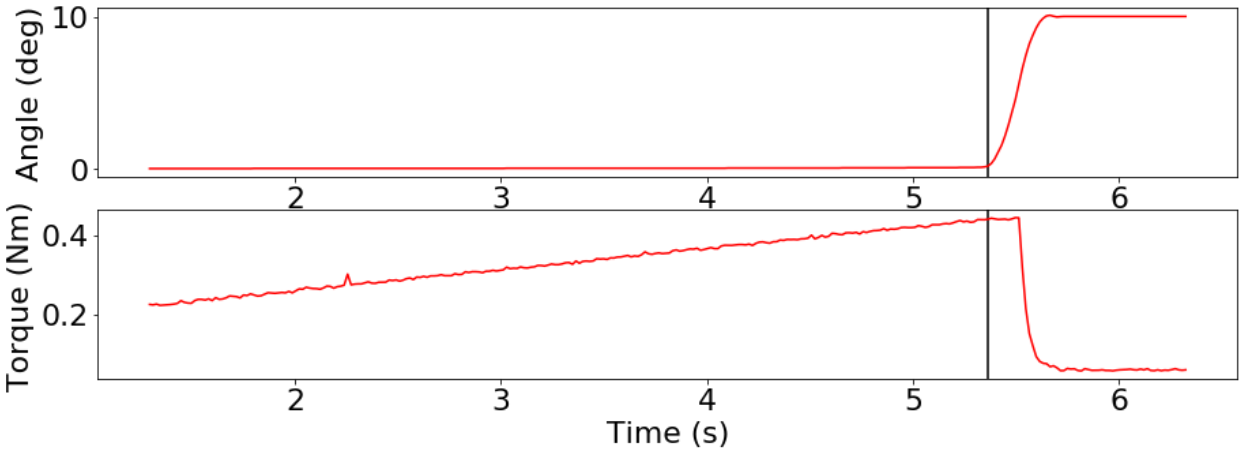

Fig. 1. Static friction identification: The top row plot shows the motor angle (red curve) and the bottom plot shows the torque applied (red line) by the current controller. The black line indicated the location when the motor just started to move (angular velocity > 0.1rad/sec) and static friction was estimated as the torque applied one-time step before.

The position, angular velocity, and the motor current were recorded during this experiment. Static friction was estimated from the current at which the motor started to move. Fig. 1 shows one such trial, where the top row plots the change in the motor angle and the bottom row shows the torque applied as a function of time. The vertical black line marks the time point when the motor just started moving (angular velocity > 0.1rad/sec). The static friction was evaluated as the torque one-time step before velocity crossed non-zero angular velocity. The static friction for any passive mechanism is obtained as the difference in the static friction with and without the mechanism attached to the motor-gearhead assembly.

Inertia and viscous damping identification

A block diagram representation of PLUTO is shown in Fig. 2. The overall inertia and the viscous damping of this system is the sum of the individual contributions of the motor-torque sensor assembly and the passive mechanism attached to the motor as shown in equation (1).

$$I\dot{\omega}_a(t) + B\omega_a(t) = \tau_a(t) \tag{1}$$

where,

- I is the overall inertia $I = I_{MT} + I_{PM}$; I_{MT} and I_{PM} are the inertia of the motor-gearhead assembly, and a passive mechanism, respectively.
- B is the viscous damping $B = B_{MT} + B_{PM}$; B_{MT} and B_{PM} are the viscous damping of the motor-gearhead assembly, and a passive mechanism, respectively.
- $\omega_a(t)$ is the angular velocity
- $\dot{\omega}_a(t)$ is the angular acceleration.

To identify I and B, a chirp input $\tau_a(t)$ (Amplitude: 0.4Nm, frequency sweep: 1Hz to 4Hz in 30sec) was applied and the angular velocity $\omega_a(t)$ was measured with a hall sensor and the angular acceleration $\dot{\omega}_a(t)$ was computed as the derivative of $\omega_a(t)$ using the Savitzky-Golay filter in the Python SciPy library (Window length = 11, polynomial order = 3). The experiment was repeated five times and the parameters (I, B) were identified through a linear least-squares fitting procedure as shown in equation (2).

$$\begin{bmatrix} I \\ B \end{bmatrix} = \mathbf{A}^{+} \cdot \boldsymbol{\tau}; \boldsymbol{\tau} = \begin{bmatrix} \tau_a(t_1) \\ \tau_a(t_2) \\ \vdots \\ \tau_a(t_N) \end{bmatrix}; \mathbf{A} = \begin{bmatrix} \dot{\omega}_a(t_1) & \omega_a(t_1) \\ \dot{\omega}_a(t_2) & \omega_a(t_2) \\ & \vdots \\ \dot{\omega}_a(t_N) & \omega_a(t_N) \end{bmatrix} \tag{2}$$

where, $\mathbf{A}^{+}$ is the Moore-Penrose pseudoinverse of A.

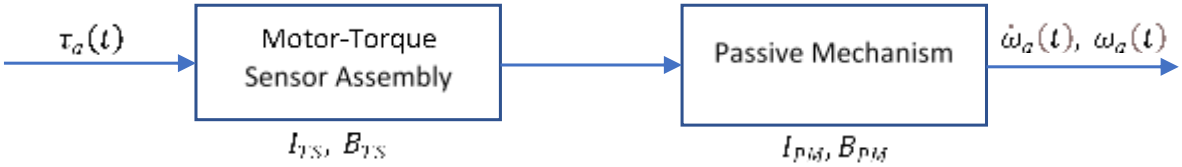

Fig. 2. Block diagram representation of PLUTO.

First, the inertia and the viscous damping of the motor-torque sensor assembly were identified without attaching any passive mechanism ($I_{PM} = 0, B_{PM} = 0$). Then experiments were carried out with each passive mechanism coupled to the motor-torque sensor. A passive mechanism's inertia and damping were obtained as the difference between the values with and without the mechanism ($I_{PM} = I - I_{TS}$; $B_{PM} = B - B_{TS}$).

Setup for step response with simulated impedance

To stimulate an impedance close to a human joint, we had used a mock setup, as shown in Fig. 3. A rubber band with known stiffness (32.2 N/m) was used to match the joint stiffness and a mass to match the joint's inertia.

For the flexion-extension and the pronation supination setup, the rubber bands were

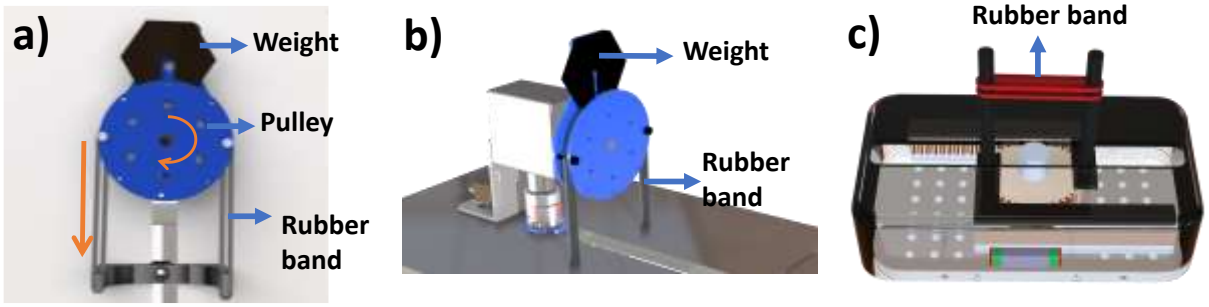

Fig. 3. Mock setup for step response. The rubber band applies a resistive torque on a pulley when the motor rotates. The weight is to match the mass moment of healthy human hand. a) Wrist flexion-extension setup b) Forearm Pronation-Supination setup c) Hand Opening-Closing setup.

attached such that at joint neutral the rubber bands are slack (apply zero torque). When the pulley rotates, the rubber band stretches and applies a resistive torque in the opposite direction. Multiple rubber bands were added to match the required joint stiffness.

For the hand opening-closing mechanism, there was no inertia component, and the rubber band was attached between the thumb and the finger holder rods to simulate the stiffness during hand opening.

System Usability Scale

Usability outcome measured by the system usability scale (SUS)

To calculate the SUS score for a subject [1], the sum of each item's scores is calculated; each item can have a value between 0-4. For items 1, 3, 5, 7, and 9: a score of zero corresponds to total disagreement and a score of four corresponds to total agreement. The reverse is true for items 2, 4, 6, 8, and 10. The sum over all the items is multiplied by 2.5 to get the final score between 0 to 100.

The SUS scores for the individual patients, caregivers, and clinicians is shown in Tables S1, S2, and S3, respectively.

Supplementary Table 1: Details of the responses to the SUS from the 15 patients following their training with the PLUTO.

		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	Mean
1	I think that I would like to use this system frequently	0	3	2	2	2	4	2	4	3	0	2	4	2	0	4	2.3
2	I found the system unnecessarily complex	3	1	4	0	4	4	3	3	3	4	1	4	3	4	1	2.8
3	I thought the system was easy to use	4	4	4	4	4	4	4	4	4	0	3	4	4	2	4	3.5
4	I think that I would need the support of a technical person to be able to use this system	4	0	4	1	0	0	1	1	4	0	0	1	0	4	2	1.5
5	I found the various functions in this system were well integrated	4	4	4	4	4	4	3	4	3	4	4	4	3	4	2	3.7
6	I thought there was too much inconsistency in this system	4	4	4	4	4	4	1	4	3	4	2	4	3	4	2	3.4
7	I would imagine that most people would learn to use this system very quickly	4	4	4	4	4	4	4	4	4	4	4	4	3	2	4	3.8
8	I found the system very cumbersome to use	4	4	4	0	3	4	2	4	3	4	4	4	3	4	1	3.2
9	I felt very confident using the system	4	4	2	3	4	4	4	3	4	4	3	4	2	2	4	3.4
10	I needed to learn a lot of things before I could get going with this system	4	4	4	2	0	4	1	4	4	0	4	0	0	3	0	2.3
	Individual SUS Score	**87.5**	**80**	**90**	**60**	**72.5**	**90**	**63**	**88**	**88**	**60**	**68**	**82.5**	**58**	**72.5**	**60**	74.5

Supplementary Table 2: Details of the responses to the SUS from the 15 caregivers.

		A1	A2	A3	A4	A4	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	Mean
1	I think that I would like to use this system frequently	2	3	4	2	4	4	3	4	3	4	3	4	4	2	4	3.3
2	I found the system unnecessarily complex	4	1	1	4	4	4	0	4	4	4	2	3	4	3	4	3.1
3	I thought the system was easy to use	4	4	4	4	4	4	4	3	2	4	0	4	4	4	4	3.5
4	I think that I would need the support of a technical person to be able to use this system	0	0	0	2	4	2	1	0	4	4	3	3	4	1	4	2.1
5	I found the various functions in this system were well integrated	3	4	4	4	4	4	3	3	2	4	2	3	4	3	4	3.4
6	I thought there was too much inconsistency in this system	4	4	2	4	4	4	0	3	2	4	2	4	2	1	2	2.8
7	I would imagine that most people would learn to use this system very quickly	4	4	4	4	4	4	4	4	4	4	2	4	3	4	3	3.7
8	I found the system very cumbersome to use	4	4	2	4	0	4	4	4	4	4	2	4	2	2	2	3.1
9	I felt very confident using the system	4	4	4	4	4	4	3	4	4	4	2	4	0	4	0	3.2
10	I needed to learn a lot of things before I could get going with this system	4	4	1	0	2	4	0	0	4	0	0	4	1	1	1	1.7
	Individual SUS Score	**82.5**	**80**	**65**	**80**	**85**	**95**	**55**	**72.5**	**82.5**	**90**	**65**	**92.5**	**70**	**62.5**	**70**	**75.2**

Supplementary Table 3: Details of the responses to the SUS from the 15 Clinicians.

		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Mean
1	I think that I would like to use this system frequently	4	2	3	4	4	3	2	0	3	3	3	2	3	2	3	2.7
2	I found the system unnecessarily complex	4	3	3	4	4	4	2	3	3	2	3	3	2	2	3	3
3	I thought the system was easy to use	3	4	3	4	4	4	2	2	3	3	4	2	2	2	3	3
4	I think that I would need the support of a technical person to be able to use this system	3	0	3	4	4	4	2	3	3	0	3	1	3	1	1	2.3
5	I found the various functions in this system were well integrated	4	3	3	4	4	4	1	4	4	2	2	3	3	3	4	3.2
6	I thought there was too much inconsistency in this system	4	4	3	4	4	4	3	3	3	1	2	3	3	2	4	3.1
7	I would imagine that most people would learn to use this system very quickly	2	3	3	3	3	4	1	4	3	3	3	1	2	1	4	2.7
8	I found the system very cumbersome to use	4	4	4	1	4	4	1	3	3	3	2	4	3	1	3	2.9
9	I felt very confident using the system	4	3	3	4	4	4	1	4	3	3	4	3	1	1	3	3
10	I needed to learn a lot of things before I could get going with this system	1	1	1	4	4	4	2	2	3	0	2	1	3	1	4	2.2
	Individual SUS Score	**82**	**67**	**72**	**90**	**97**	**97.5**	**42.5**	**70**	**77.5**	**50**	**70**	**57.5**	**62.5**	**40**	**80**	**70.5**

User Experience Questionnaire (UEQ)

The UEQ contains 6 subscales with 26 items, which are scores between -3 to +3; -3 represents the most negative answer, 0 a neutral answer, and +3 the most positive answer. Questions for each subscale is given below:

1) **Attractiveness**: annoying / enjoyable, good / bad, unlikable / pleasing, unpleasant / pleasant, attractive / unattractive, friendly / unfriendly
2) **Efficiency:** fast / slow, inefficient / efficient, impractical / practical, organized / cluttered
3) **Perspicuity:** not understandable / understandable, easy to learn / difficult to learn, complicated / easy, clear / confusing
4) **Dependability:** Items: unpredictable / predictable, obstructive / supportive, secure / not secure, meets expectations / does not meet expectations
5) **Stimulation:** Items: valuable / inferior, boring / exiting, not interesting / interesting, motivating / demotivating
6) **Novelty**: Items: creative / dull, inventive / conventional, usual / leading edge, conservative / innovative

The following figure (Fig. 3) shows the question wise mean scores of the patients and clinicians. Values between -0.8 and 0.8 represent a neutral evaluation of the corresponding scale, values > 0,8 represent a positive evaluation and values < -0,8 represent a negative evaluation. Only the question “Slow/fast” had a negative evaluation of -0.4 by the patients. Twenty-one of the 26 questions had a positive evaluation by both the patient and clinician.

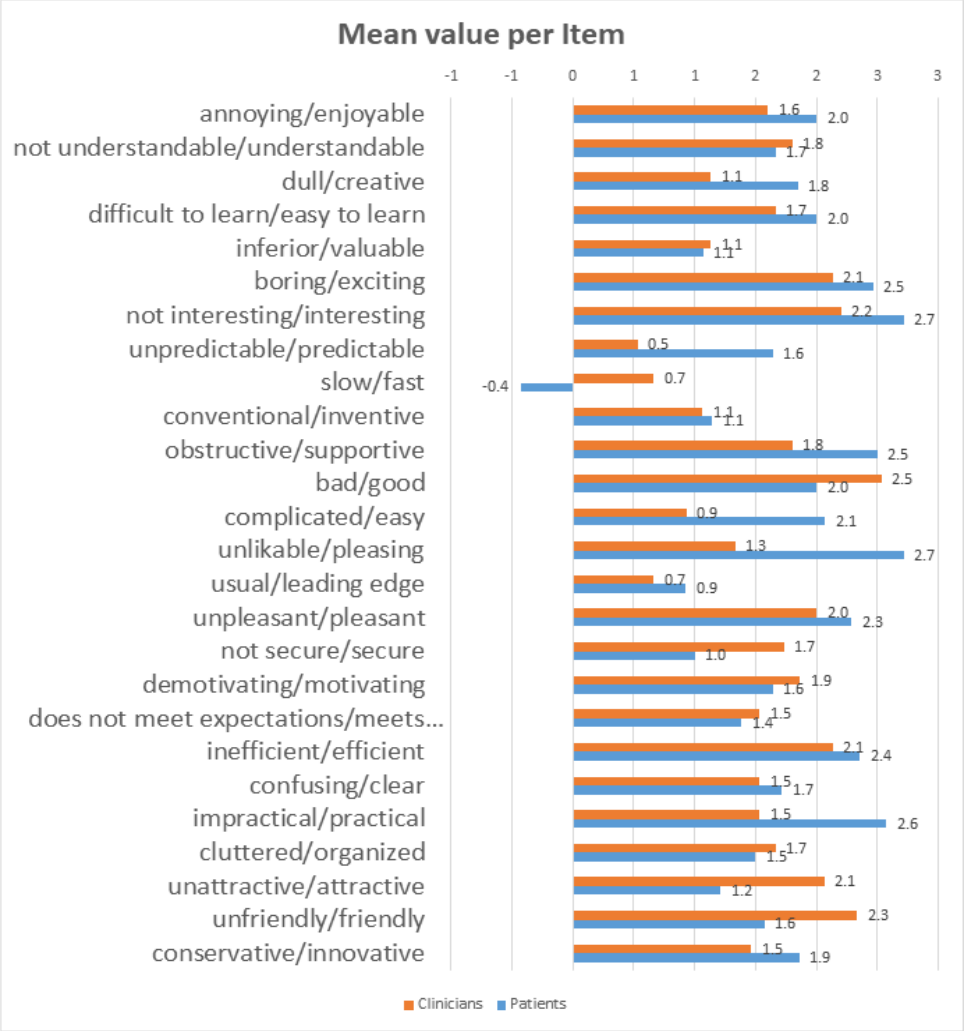

Fig. 3. User experience questionnaire: Question-wise mean score. Each question had a range of -3 to +3. Where -3 is the lowest negative rating and +3 is a highest possible positive rating. The orange bar graph shows the mean elevation from the clinician group and the blue bar graph shows the mean evaluation from the patient group.

Supplementary Table 4: Details of the responses to the UEQ subscales from the 15 Clinicians.

	Scale means per person					
	Attractiveness	**Perspicuity**	**Efficiency**	**Dependability**	**Stimulation**	**Novelty**
C1	3.00	1.00	2.50	2.50	1.50	1.50
C2	0.67	1.00	1.25	0.75	1.50	0.75
C3	2.50	1.50	2.50	2.00	2.50	2.50
C4	3.00	2.75	2.25	2.25	3.00	3.00
C5	2.83	3.00	2.75	2.00	2.75	2.25
C6	3.00	3.00	3.00	2.25	3.00	1.50
C7	1.00	0.50	0.25	0.75	0.75	1.25
C8	2.50	2.50	2.50	2.25	2.50	1.75
C9	2.00	2.00	1.25	1.25	2.25	1.25
C10	1.67	-0.25	-0.50	0.50	0.75	-0.75
C11	0.67	0.50	0.75	0.25	0.75	-0.50
C12	2.50	2.50	2.50	2.25	2.50	1.75
C13	2.00	2.00	1.25	1.25	2.25	1.25
C14	1.67	-0.25	-0.50	0.50	0.75	-0.75
C15	0.67	0.50	0.75	0.25	0.75	-0.50

Supplementary Table 5: Details of the responses to the UEQ subscales from the 15 patients.

	Scale means per person					
	Attractiveness	**Perspicuity**	**Efficiency**	**Dependability**	**Stimulation**	**Novelty**
P1	2.00	2.25	1.75	1.75	2.50	0.00
P2	2.50	3.00	1.25	1.50	2.25	2.50
33	2.83	2.00	2.00	1.00	1.50	2.75
P4	3.00	-0.50	0	0	0	3.00
P5	2.83	2.67	0.75	2.50	2.67	1.00
P6	1.83	3.00	1.75	3.00	3.00	-3.00
P7	2.33	2.50	2.50	2.25	2.25	2.25
P8	1.17	2.25	-0.25	1.50	1.25	2.75
P9	2.83	2.75	3.00	1.50	2.75	3.00
P10	2.83	2.50	2.50	2.00	2.50	3.00
P11	-0.17	-0.25	0.00	-1.50	-0.25	0.00
P12	-0.17	0.00	0.50	0.50	0.50	0.00
P13	1.67	-0.50	1.50	1.75	2.25	2.00
P14	2.17	2.50	2.00	2.75	3.00	1.25
P15	2.67	2.75	1.75	2.25	2.75	1.00

UEQ reliability

Guttman's lambda-2 [2] was used to measure the reliability/internal consistency of the questionnaires . λ2 quantifies how well their scores can differentiate test-takers. If test-takers differ significantly in their abilities, λ2 will be high, and the error will be low. Values λ2 > 70% [3] is considered reliable for group-level studies.

Supplementary Table 6: Reliability of UEQ

	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty	Overall
Patients	0.79	0.74	0.5	0.53	0.59	0.67	0.64
Clinicians	0.85	0.81	0.76	0.63	0.55	0.54	0.69
Mean	0.82	0.77	0.63	0.58	0.57	0.60	0.67

References

[1] J. Brooke, "SUS-A quick and dirty usability scale," *Usability Eval Ind*, vol. 189, no. 194, pp. 4–7, 1996.

[2] H. G. Osburn, "Coefficient alpha and related internal consistency reliability coefficients.," *Psychol Methods*, vol. 5, no. 3, pp. 343–355, 2000.

[3] S. C. Peres, T. Pham, and R. Phillips, "Validation of the system usability scale (sus): Sus in the wild," *Proc Hum Factors Ergon Soc*, no. September 2013, pp. 192–196, 2013.