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Supplementary Materials for

An anthropomorphic soft skeleton hand exploiting conditional models for piano playing

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The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

(available at robotics.sciencemag.org/cgi/content/full/3/25/eaau3098/DC1)

Supplementary Materials

CAD, Hand Design and 3D Printing

The hand has been designed using an anthropomorphic hand model, which has then been adapted using the CAD software 3DS Max. The ligament design has been simplified to reduce the number of variables, with the joints modelled as ellipse shells (Fig. S1). The shell thickness has been designed such that the ligaments are sufficiently strong to prevent ripping or tearing and prevent weakness of the joint.

The 3D printer used is a Stratasys Connex 5000, which prints the material in layers, with UV light used to cure the liquid material deposited. This requires a solid model to be produced, with support material printed in locations where there is not material, for example within he ligaments shells in the areas where bones interact. To remove the support material from inside the joints there must be access for the chemical solvent used, and thus small relief holes are used in the undersides of the joints (Fig. S1.)

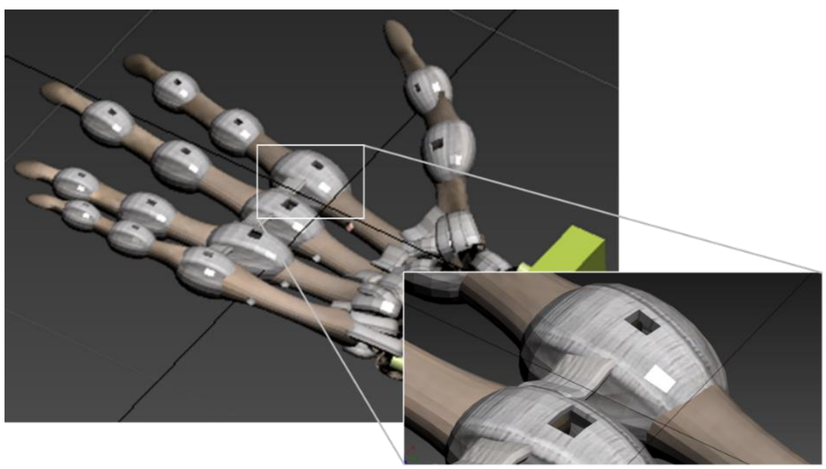

Fig. S1. Hand CAD model showing the finger ligament designs. Hand CAD model showing the finger joint design, with the inset picture showing how the softer ligament material has square cut outs to allow the support material to be removed from the joint area after printing.

The different blends of materials and the properties used are shown in Table S1. There are four different ligament materials with varying blends of Tango Black and rigid plastic which are used in experiments. The fused deposition 3D printing methods requires the use of support material in the fabrication such that the hand can be printed in layers. The support material must be removed from the hand using a combination of mechanical removal and chemical removal.

Table S1. 3D-printed materials used and their material properties. Includes the ligaments of different stiffnesses, and the bones. Shows the blend of blasé materials used to generate the materials with a given stiffness.

	Tango Black Percentage (%)	Agile White Percentage (%)	Shore Hardness	Young's Modulus (E)
Ligament (least stiff)	100	0	A97	1 MPa
Ligaments	90	10	A75	2.5 MPa
Ligaments	80	20	A50	20 MPa
Ligaments (most stiff)	70	30	A25	50 MPa
Bones	0	100	-	2GPa

Experimental Setup

The full experimental setup is shown in Fig. S2. A UR5 robot, which offers 6 degrees of freedom, is used to provide the wrist actuation. The 3D printed hand is mounted securely on the end of the arm using bolts.

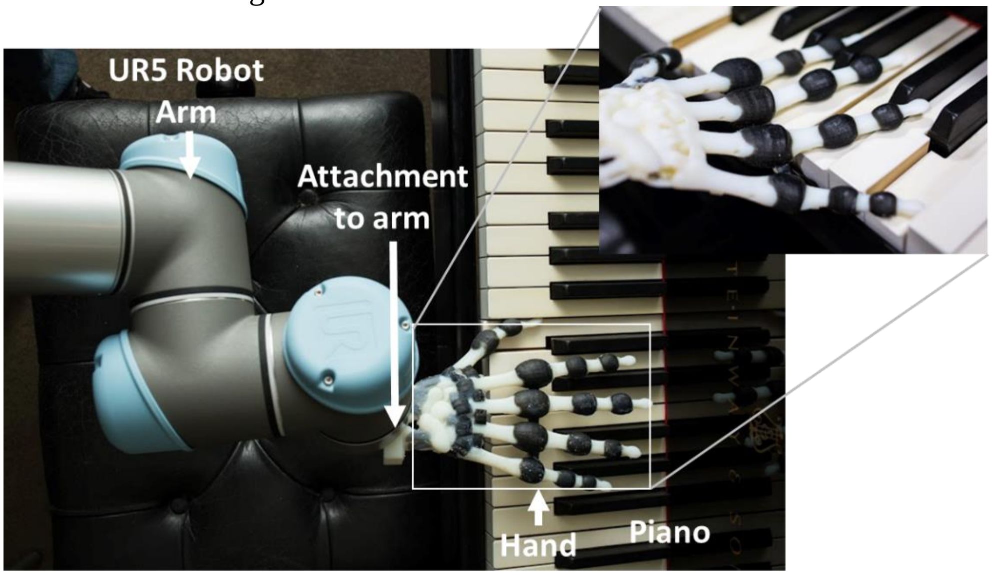

Fig. S2. Full experimental setup. Showing the UR5 Arm. The attachment of the hand to the arm and the 3D printed hand. The UR5 arm is placed such that it is perpendicular to the environment, which is in this case the piano.

A block diagram of the implementation of piano playing is shown in Fig. S3. The inputs (music, mechanical properties, environmental properties and a database of known note locations and transitions) are input into a planner, which determines the control parameters and required locations. The UR5 arm controller is used to determine the inverse kinematics and then control the UR5 Arm. This allows the hand to be moved relative to the environment, with the Conditional Stiffness, giving rise to output behavior in the form of piano playing.

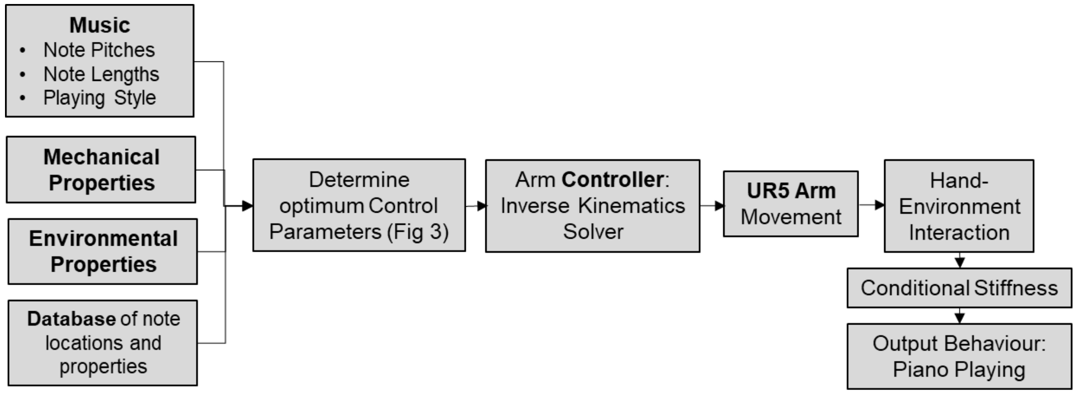

Fig. S3. Block diagram of the system for piano playing. Showing the inputs, planning system and the overall output, piano playing.

Anisotropic Hand Stiffness

Experimental Methods

To measure the compliance of stiffness of the individual finger, the finger was mounted in a fixed position horizontally. A known force is then applied to the finger-tip, and the displacement between the center line of the finger and the displaced finger tip-measured. This method is shown in Fig. S4. The compliance of the finger can then be determined:

$$Compliance_{angle} = \frac{Force\ Applied}{\Delta z}$$

This method can be extended to investigating the directional stiffness of the thumb joint and also the finger joints around other planes of rotation.

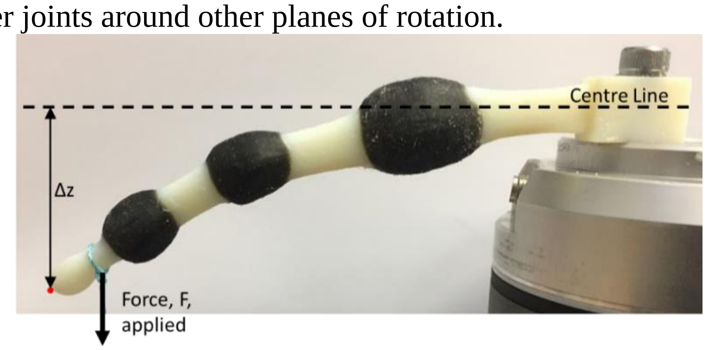

Fig. S4. Experimental method to determine the compliance of a single finger. The three joints of the finger are used, with the finger fixed at a given orientation. A force is applied with the displacement of the finger tip in the direction of the force measured.

Passive Hand Compliance

The thumb is particularly complex due to the ability of the thumb joint to distend, and the complex network of ligaments used to construct the joints gives rise to stiffness, which is highly direction.

The 3D printer materials, blends of materials and their used shore hardness and Young's Modulus is shown in Table S1. Three behavior primitives are presented in this paper: single note playing, thumb abduction and chord spreading. These behavior primitives form the basis of many different hand playing morphologies and structures.

Arm Actuation

Inverse kinematics of the UR5 is used to allow control of the end effector in Cartesian co-ordinates. The considered control parameters include the position of the end effector and the corresponding velocities:

$$W = \begin{bmatrix} x & y & z \\ \alpha & \beta & \gamma \end{bmatrix}$$

$$\dot{W} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{z} \\ \dot{\alpha} & \dot{\beta} & \dot{\gamma} \end{bmatrix}$$

We consider the following parameters for the corresponding elements of piano playing:

Table S2. Summary of arm control parameters. The dependency of wrist parameters on playing behaviour and the dependency of this on material hand properties.

Music Playing Behaviour	Wrist Parameters	Dependency on Hand Properties
Note pitch (note location)	x,y	-
Note length	T	-
Articulation (legato/staccato)	$\dot{z}$	E_J
Volume	Δz	E_J
Abduction/Adduction distance	$\Delta x,$	E_T
Single Finger span movement	Δx	E_S
Angled Hand Playing	α	E_S

The specific arm actuation and motion planning used for the three pieces played, are summarized in the following section with the motion planning represented in a flow chart with the specific actuation principles provided which corresponding to the elements in Table S2.

Toccata, Scarlatti

Requires the repeated staccatto playing using the **third finger** with has a stiffness **E_J of 50MPa**.

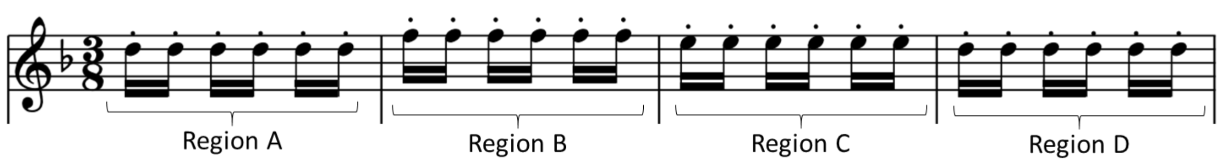

Fig. S5. *Toccata* music separated into regions. The 4 different regions of the music which have different playing positions.

The motion planning is summarized by the flow chart in Fig. S6. with the corresponding parameters given in Table S3. For the twenty experimental repetitions of the playing there was 100% in the hand performing the piece, with no piano keys missed.

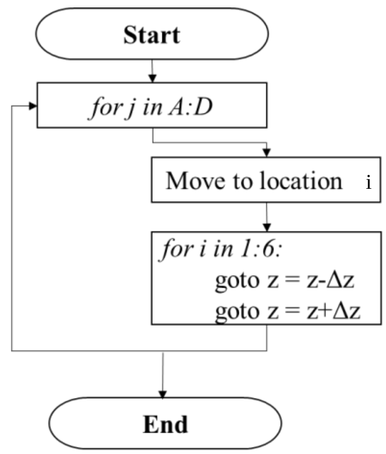

Fig. S6. Flow chart of the motion planning required for playing *Toccata*. Repeated note playing a the four different locations.

Table S3. Summary of arm parameters used in the arm control for playing *Toccata*.

Music Playing Behaviour	**Wrist Parameters**	**Values**
Note pitch (note location)	Starting Location, Region (A) (x,y,z) Region (B) (x + 27,y,z) Region (C) (x + 13.5,y,z) Region (D) (x,y,z)	"x": -78.18, "y": -81.50, "z": 120.22
Articulation (legato/staccato)	$\dot{z}$	0.25m/s
Volume	Δz	15mm

Alligator Crawl, Fats Waller

The Alligator Crawl music uses two fingers for playing, the thumb and little finger. The thumb is used to play the lower note and then the little finger the higher note in each pair. There are five different locations (A-D) in which the pattern is repeated. The thumb stiffness, E_J, is low to help enable travelling between the two notes, as is the span stiffness. The little finger is angled to help achieve sufficient force when playing. For the twenty experimental repetitions, due to the accumulation of erroring the drift of position of the arm, of the many times the little finger was used to play the higher notes, in 4% of cases, there was a mis-played note.

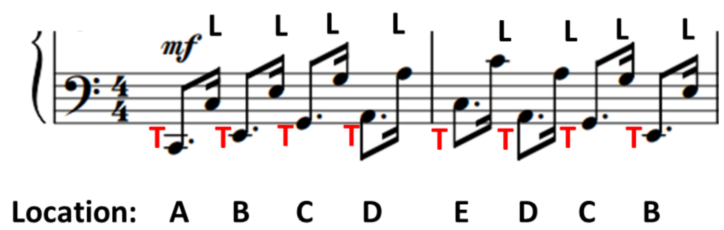

Fig. S7. *Alligator Crawl.* Showing which fingers are used to play different notes (thumb, 'T', or little finger, 'L') with different locations, which are repeated throughout the musical phrase.

The flow chart summarizing the motion planning for playing Alligator Crawl is given in Fig. S10.

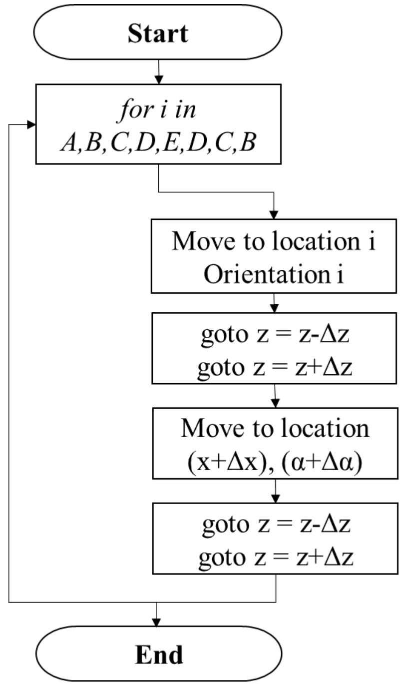

Fig. S8. Flow chart for *Alligator Crawl*. Shows the motion planning for the sequence. Corresponds to Table S4, which specifies the specific magnitudes.

Minor manual adjustment of the motion plan was required – in particular when stepping down note locations (e.g. when travelling from locations E-D-C-B).

Table S4. Summary of arm parameters used in the arm control for playing *Toccata*.

Music Playing behavior	**Wrist Parameters**	**Values**
Note pitch (note location)	Starting Location, (A) (x,y,z,α) B=(x+27,y,z) C=(x+54,y,z) D=(x+81,y,z) E=(x+108,y,z)	"x": -72.93, "y": -67.50, "z": 130.29,
Articulation (legato/staccato)	$\dot{z}$	$0.2 m/s$
Volume	Δz	17mm
Abduction/Adduction distance	$\Delta x,$	~5mm
Single Finger span movement	Δx	~5mm
Angled Hand Playing	α	Thumb = -5° Little Finger 35°

Rhapsody in Blue, Gershwin

Rhapsody in Blue is all played with the thumb, with the abduction of the thumb used to allow smooth glissando playing between notes. For the twenty experimental repetitions of the playing there was 100% in the hand performing the piece, with no piano keys missed.

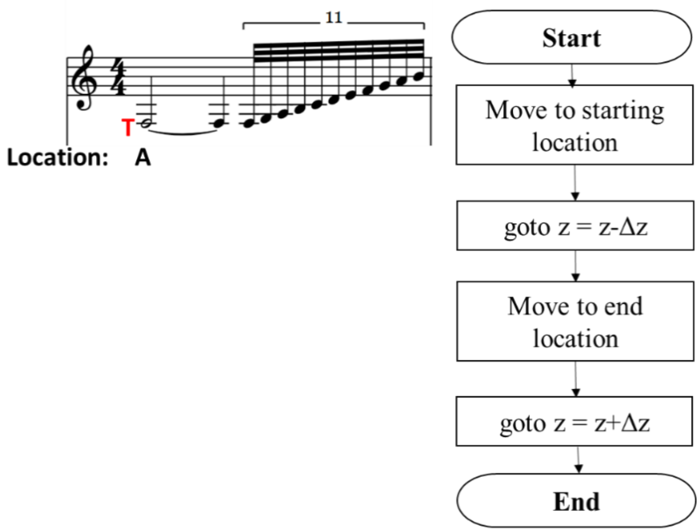

Fig. S9. Adapted music for *Rhapsody in Blue* and motion planning flowchart. Shows the motion planning for the sequence, with the specific values of parameters given in Table S5.

Table S5. Summary of arm parameters used in the arm control for playing *Rhapsody in Blue*.

Music Playing Behavior	**Wrist Parameters**	**Values**
Note pitch (note location)	Starting Location: (x,y,z α) End location: (x,y,z α)	"x": -72.93, "y": -67.50, "z": 130.29,
Volume	Δz	17mm
Abduction/Adduction distance	$\Delta x,$	~5mm

Video Files

Movie S1. Fabrication. Video showing a time lapse of the 3D printing process for the hand showing how a hand can be printed in a single prin. Shows the flexibility of the hand once produced and the passive dynamics.

Movie S2. Single-finger behavior. Shows the range of movement of a single finger and the response from fingers of different stiffness when provided with the same vertical movement to play a single note showing the variation in resultant morphology and also output sound.

Move S3. Abduction/adduction behavior. Demonstrates abduction and adduction behavior of a single hand and the range of piano playing this enables.

Movie S4. Hand span playing behavior. Playing with the hand at angles allows jumps of various intervals to be made.

Movie S5. Three pieces of music playing. Using a single 3D printed hand to play music of different styles and forms. Show different camera views from different repeats of the experiment.