CordChord: A String Instrument with Optical Sensing

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ABSTRACT

This paper introduces *CordChord*, a hybrid musical instrument that sees the performer interact with two physical cords to control the pitch, amplitude, and timbre of a two-voice granular synthesiser. An existing method for tracking bowing parameters of string instrument performance is adapted to measure the displacement of the cords by the performer's fingers. The method is based on an array of optical distance sensors in combination with a regression machine learning model to predict the position at and the amount by which each cord is displaced from a baseline tensioned position. Capacitive strips on the back of the neck of the instrument afford additional timbral control. A preliminary user study suggests that performers find the system responsive and engaging to play, while highlighting the need to further improve the accuracy of the regression model to make the system more intuitive.

Author Keywords

Musical Interface, String Tracking, Optical Sensing, Capacitive Sensing

CCS Concepts

•**Applied computing** → **Sound and music computing; Performing arts;** •**Human-centered computing** → *Interaction devices;*

1. INTRODUCTION

CordChord[1] is a novel string-based interactive music system with which the performer uses their fingers to displaces two identical and independent 'cords' towards the 'neck' of the instrument to continuously control the pitch and amplitude of a two-voice granular synthesiser. As these parameters are unquantised, extended techniques, including vibrato and tremolo, can also be achieved. Two capacitive strips on the back of the neck controlled using the thumbs provide additional timbral control.

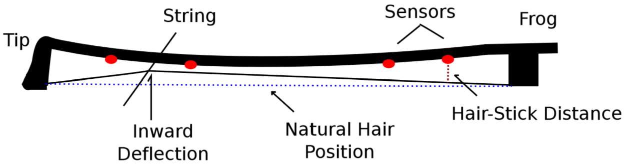

Figure 1: The sensor placement on the bow, reprinted from Pardue et al. [2]. The readings from the sensors define a unique 'displacement triangle' which describes the displacement of the bow hair from its baseline tensioned position. The peak of the displacement triangle is the bow position, while the height of the triangle is determined by bow force. Bow velocity is derived from position.

Unlike an acoustic string instrument, the cords of the instrument do not vibrate nor is there a resonating body, therefore the instrument responds solely on parameters estimated from the displacement of the cord from a baseline position to control pitch and amplitude. The CordChord gets its name from a wordplay: "Cord" refers to the 'strings' of the prototype, while "chord" highlights its unique ability to play chords, a feature not commonly found in conventional string instruments.

The instrument builds on previous work by Pardue et al. [1, 2] on tracking bowing parameters during string instrument performance, and applies it to a novel musical interface. Pardue et al. propose a low-cost and simple solution for tracking bow position, bow velocity, and bow force using four optical distance sensors attached to the underside of the bow stick facing towards the bow hair. When the bow is pressed into the string, every combination of bow position and bow force results in a unique combination of stick-hair distances measured by the optical distance sensors. This logic is shown in Figure 1. A regression model is then trained to learn the corresponding bow position and bow force from the distance sensors data.

In CordChord, we adopt this methodology to instead model the displacement of each cord of the instrument towards the neck. While Pardue et al. measure bow force directly when generating the dataset to train their regression model [2], we estimate the neck-cord distance (NCD) as a proxy for force. This change negatively affects the performance of the model at the ends of the cords, but nonetheless demonstrates that the method remains viable with only basic components. To avoid ambiguity, 'cord' hereafter refers to the strings of CordChord, while 'string' is used when discussing the bow tracking approach.

CordChord also pulls inspiration from other string-based interactive music systems, which have been the subject of significant research in the field of interactive novel interfaces for musical expression.

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[1] `https://github.com/hathuwic/CordChord`

NIME'24, 4–6 September, Utrecht, The Netherlands.

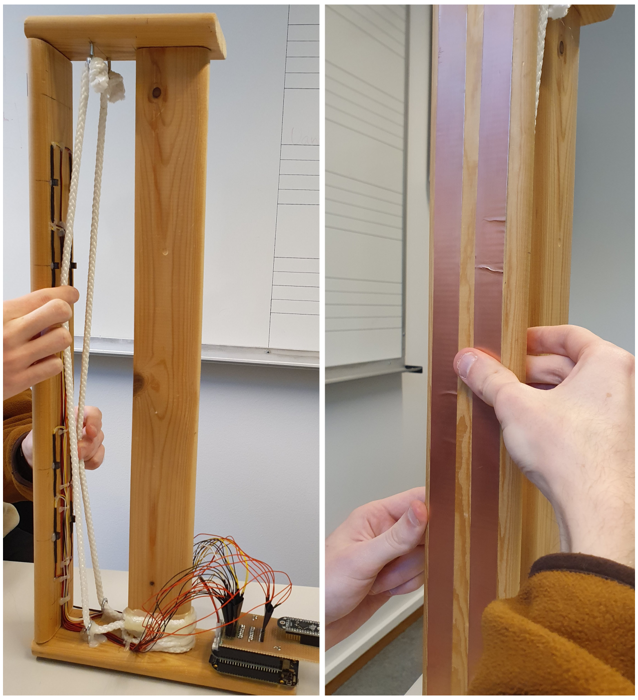

Figure 2: The intended usage of CordChord. The performer rests their thumbs on the back of the neck, and pulls the cords towards the neck with their fingers. The capacitive strips on the back of the neck are operated using the thumbs.

Extended or electronic violins aiming to capture performance gestures as mapping parameters have been extensively explored [3, 4, 5]. Similarly, different means of interacting with strings have been examined in [6, 7, 8].

Others have proposed approaches for tracking bowing parameters of acoustic string performance utilising a variety of technologies including resistance wires, strain gauges, and optical motion capture systems [9, 10, 11, 12].

However, the low-cost and ease of implementation of the approach proposed by Pardue et al. offer a suitable method for real-time interaction with strings. In CordChord, we replace the bow hair with a 'cord' and the bow stick with the 'neck' of the wooden frame, then adopt the same approach to determine the position and amount of displacement of the cord. CordChord features two independent cords, which are each tracked with an independent array of optical distance sensors. This represents the first real-time application of this tracking approach, which we use as part of an interface for musical expression designed to be engaging and intuitive in its own right.

Regarding harmony, as the cords are independent, the performer can displace them at different positions to voice two different pitches simultaneously, thereby outlining chords.

Through a preliminary user study, we show that, while the system is responsive and broadly intuitive for performers, key areas for improvement remain including the linearity of pitch response and accessibility of amplitude and timbral control.

2. DESIGN & IMPLEMENTATION

CordChord consists of two sensing methods: the displacement of the cords to control pitch and amplitude of the synthesized sound generation; and capacitive strips on the back of the neck to control timbre. The hand posture while using the instrument is shown in Figure 2.

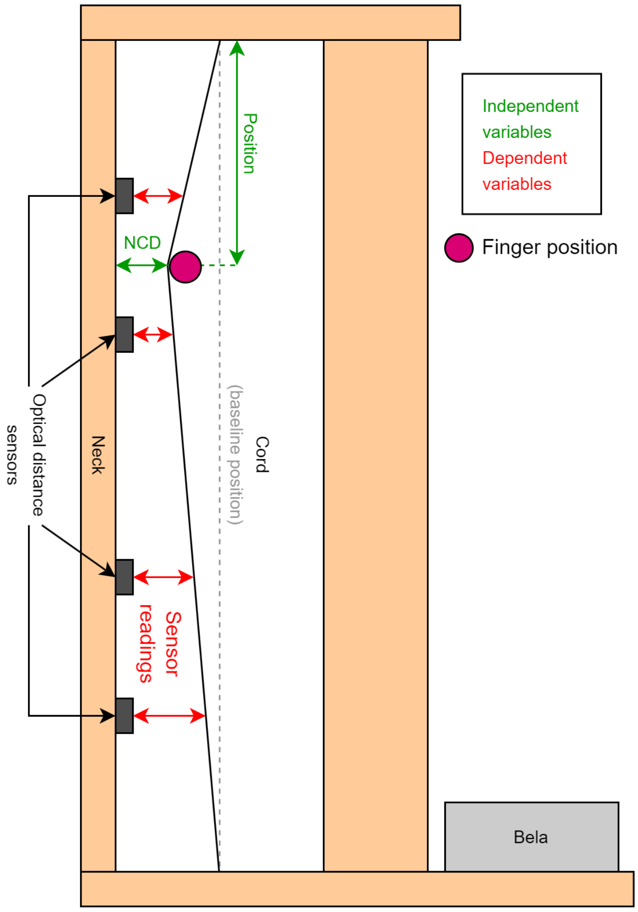

Figure 3: The side schematic view of CordChord, showing one of the two cords, and the position and neck-cord distance (NCD) parameters predicted by the regression model.

The method used by Pardue et al. [1] for bow tracking provides a suitable starting point for tracking the displacement of the cords in CordChord. We predict two discrete parameters of the behaviour of each cord of each cord, which are visualised in Figure 3:

(a) the position of the contact point between the cord and the performer's finger(s) along the length of the cord. This is analogous to the contact point between the violin string and the bow hair in Figure 1.

(b) the displacement of the cord towards the neck, from its baseline position at the contact point. We refer to this parameter as the neck-cord distance (NCD). This is analogous to the bow hair displacement at the contact point, and therefore bow force, in Figure 1.

The position is mapped linearly to the MIDI pitch of each cord, similarly to the ondes Martenot [13], while the displacement amount corresponds linearly to that cord's amplitude. This mapping also facilitates extended techniques. For example, vibrato and tremolo are attainable by varying either position or displacement rapidly during performance. Similarly, slow variations in finger position create glissandi, and varying displacement at different speeds allows for both slow dynamic changes and short transients.

The capacitive strips on the back of the neck utilise this spare physical bandwidth of the performer's thumbs to provide additional timbral control. By adjusting the size of the contact patch between the thumb and the strip, the performer can vary the grain size of the granular synthesis

Figure 4: The CordChord. Left: The side profile showing the rectangular wooden frame with 2 'cords' of polyester rope fixed between the short sides. Right: A closer view of distance sensors mounted on the neck facing towards the cords.

sound engine, resulting in either a more granular or sustained sound. This interaction is shown in Figure 2.

The main frame of CordChord consists of 4 hand-sawn planks of wood nailed together into a long rectangle shape. The frame accommodates two cords of 500mm in length attached using metal hooks. The capacitive strips are fixed to the back of the neck. The sensor data is captured and the mapping to the sound engine is implemented on a Bela board [14] which sits on the base plank.

Figure 4 shows the side profile of CordChord and the sensor placement on the neck.

The architecture and data flow of CordChord is illustrated in Figure 5, and its components are detailed in Sections 2.1-2.2.

2.1 Cord Tracking

Four QRD1114 optical distance sensors [15] are mounted on the frame as shown in Figure 4. The output voltages from the sensors are sampled by the analog inputs of Bela.

As the physical and mechanical design of each cord is symmetric, the dataset was collected on only one cord, with the intention of using a separate instance of the same trained model for each cord. Each dataset example consists of the position and NCD as independent variables, and 4 measurements from the optical distance sensors for the cord as the dependent variables. An dataset example is shown in Table 1, while Figure 3 shows the schematic side profile of CordChord, indicating the measurements included in each dataset example.

Examples were collected at 20mm intervals along the length of the cord, and at NCD increments of 5mm as far as string tension allowed, totaling 288 combinations. The dataset was recorded in near complete darkness to minimise the effects of ambient light on the sensors. The cord was held in position using a finger, which limited accuracy. The final dataset consists of 2890 examples, and is plotted in Figure 6.

We model the displacement of each cord using an artificial neural network using the Neuralnet Pure Data external [16][2], which takes as input the readings from the four sensors, and outputs the predicted position and NCD. The selected model is a fully connected network with 3 hidden layers of 48, 64, and 24 neurons respectively, sigmoid activation on hidden layers and linear activation on the output layer. The model is trained for 3000 epochs using Adam optimizer with learning rate of 0.005 and a decay of 0.001. 90% of the shuffled dataset is used for training, and 10% for testing. The selected architecture maximises the perceived linearity of the position/pitch axis, and the accuracy at the end of the cords, presenting an MSE loss of 0.009. Perceptually, the model is most accurate towards the middle of the strings, and at higher NCD values. It is less accurate towards the ends of the string due to the limited NCD range in this areas, causing some regions to not be bijective.

CordChord includes a calibration algorithm to compensate for the effect of natural light on the optical distance sensors. The algorithm calculates the mean of the first 100 samples from each sensor after booting up the system, assuming these values represent the cords in their baseline position. Each sensor reading is scaled to the expected range based on the calibration values, ensuring that the system always responds predictably to performer input regardless of the ambient lighting conditions. The network was trained with a dataset with values in the range 0-0.68, therefore sensor values S_n are scaled as follows:

$$S_n = S_n / (\frac{1}{100}\sum_{n=1}^{100} S_n) * 0.68 \tag{1}$$

Two instances of the trained networks are loaded, with one for each cord. Sensor readings are sampled every 50ms as a trade-off between instrument responsiveness and bounding the computational load.

2.2 Capacitive Sensing

The capacitive strips shown in Figure 7 are connected to the Bela board via a TrillCraft capactive sensing module. The wires connecting the copper strips to the capacitive sensing module are routed next to one another, causing interference between the two. A scaling algorithm as shown in Algorithm 1 is used to ensure the response characteristic of the strips is maintained regardless of whether the performer is touching one or both strips.

Algorithm 1 The capacitive sensor scaling logic. When only one capacitive strip C_n is touched, the maximum reading from that strip, $max(C_n) = 0.63$, while touching both strips results in $max(C_n) = 0.76$ for both strips. As a result, when the sum of the readings from both capacitive strips exceeds 0.63 i.e., $C_1 + C_2 > 0.63$, it is assumed the performer is touching both strips.

```
procedure ScaleCapactiveSensors($C_n, C_1, C_2$)
    if $C_1 + C_2 > 0.63$ then
        $C_n scaled = C_n * \frac{1}{0.76}$
    else
        $C_n scaled = C_n * \frac{1}{0.63}$
```

2.3 Sound Engine

The sound engine of CordChord consists of a two-voice granular synthesiser utilising a cello sample and a stereo delay

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[2] `https://github.com/alexdrymonitis/neuralnet`

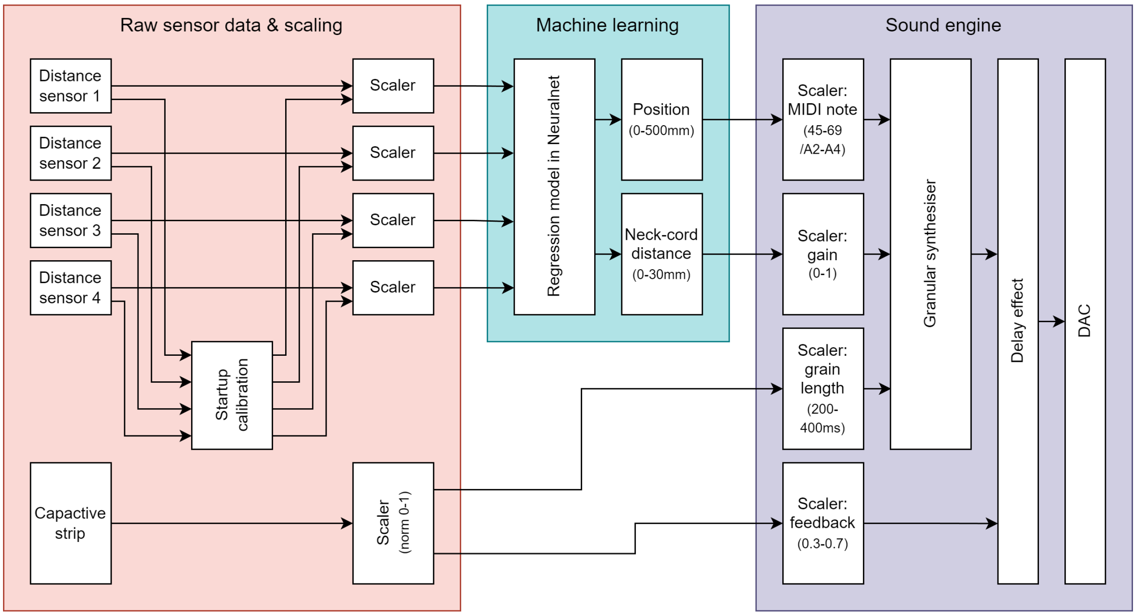

Figure 5: CordChord architecture and dataflow. The pipeline is split into 3 sections: raw sensing data and scaling, machine learning predicting human-cord interaction parameters, and mapping to the sound engine.

Pos (mm)	NCD (mm)	Sensor 1	Sensor 2	Sensor 3	Sensor 4
160	10	0.653256	0.627671	0.253395	0.63088

Table 1: An example from the collected dataset. Position and neck-cord distance (NCD) are independent variables, while sensor readings are dependent variables.

effect. The physical interface of the system can theoretically be mapped to any sound engine offering pitch, amplitude, and timbral control. Each voice of the granular synthesiser corresponds to a cord of the instrument. The pitch of each new grain is linearly derived from the current predicted position of the corresponding cord as an unquantised MIDI pitch in the range A2-A4, while the amplitude is linearly mapped from the predicted NCD from the chord. A linear mapping was qualitatively found to provide a natural amplitude response across all NCD values.

The scaled readings from the capacitive strips are mapped to the grain length of the corresponding granular voice in a range of 200-400ms. When the performer's thumb does not touch the strip, the individual grains in the corresponding voice are shorter and thus audibly 'grainy', while a large contact patch between the thumb and the strip results in longer grains and thus a more sustained, legato tone. Full technical details and a video demo and performance are available online[3].

3. EVALUATION

The system is evaluated through a preliminary user study, while further discussion is provided by the authors in Section 4.

We considered the performer as the primary stakeholder in the user study [17]. Understanding the playability of the system was a key aim, therefore both the accuracy and intuitiveness of the cord mapping were evaluated. We adopted the task-based evaluation approach from the HCI field [18].

Three tasks encouraged the participants to play the instrument in three different ways: a sustained note task; a short note task; and a musical scale task.

The study comprised four sections:

1. An 5-minute unstructured session for the participant to familiarise themselves with the instrument
2. Two simple tasks: to find and sustain three provided pitches (the sustained note task), and to find and repeatedly play one provided pitch as short notes (the short note task)
3. One complex task: playing a major scale above a given tonic
4. A second unstructured 5-minute session for the participant to explore the instrument further and experiment with extended techniques

Rating prompts were asked after each task. The additional prose prompts were included to understand the participants' enjoyment and engagement with the system, and to qualify any shortcomings of the instrument identified through the rating prompts. The results of the nine rating prompts are provided in Table 2.

The sustained note task (Q3) was considered facile by all participants, while the tasks requiring short notes and changing pitches (Q4, Q5, Q8) were more difficult. Despite the capacitive strips being at the natural thumb position during performance, the participants did not find them to be integral to their experience (Q9). However, all participants found CordChord 'intuitive', 'engaging', and 'responsive'. One commented on the physical robustness of the instrument, while two noted the lack of perceived linearity of the pitch mapping along the cord length.

4. DISCUSSION

From a month of playing with the instrument, the first author also notes that the non-linearity of the pitch response at the ends of the cords reduces playability and shrinks the

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[3] `https://github.com/hathuwic/CordChord`

Table 2: The rating results from 3 users assessing CordChord through nine questions rating their experience on a 1-7 Likert scale against several aspects, and through four prose prompts to obtain subjective feedback. All participants were music technology students but not string instrument players.

Section	Prompt	P1	P2	P3
1	Q1: Understanding of basic interactions	6	6	6
1	Q2: Engagement to learn more	6	7	7
2	Q3: Ease to hold pitches	6	7	7
2	Q4: Ease to find and release pitches	6	2	6
3	Q5: Ease to play a major scale	3	5	7
4	Q6: Responsiveness to gestures	6	6	5
4	Q7: Engagement and enjoyment of playing	7	7	6
4	Q8: Facility for rhythmically complex music	7	5	3
4	Q9: Importance of capacitive strips	3	4	2

accessible pitch range. The cords also gradually lose tension, resulting in errors in the predicted position and NSD which can cause the instrument to sound unexpectedly. The capactitive strips are currently under-utilised as they have a minimal effect on the sound produced. Despite these shortcomings, the instrument remains engaging. The pitch mapping feels familiar, while the amplitude mapping offers a new challenge. The scope for extended techniques including vibrato and tremolo, and for outlining harmony using both cords, encourage long-term engagement and raise the skill ceiling significantly.

5. CONCLUSIONS

This paper described CordChord, a novel hybrid musical string instrument in which the performer-instrument interaction paradigm is based on displacing the two parallel cords, rather than vibrating them or exciting a resonating body. The cords control a two-voice continuous-pitch granular synthesiser utilising a cello sample and a stereo delay. The instrument applies a method designed for bow tracking of string instruments to interpret how the performer interacts with the cords. This approach is shown to be relatively effective for a real-time interactive implementation, while a preliminary user study demonstrates that it is engaging and intuitive as a gestural input mechanism. Further studies are necessary for a deeper evaluation of the system, and for eventual variations arising from the results of this study.

6. ETHICAL STANDARDS

The user study was carried out in accordance with the ethical standards of the University of Oslo. No personal or demographic information was collected from participants, and no photography, video, or audio was recorded during the study. The Bela, TrillCraft module and optical distance sensors were provided by the University of Oslo. The authors report no conflicts of interest in this project.

CordChord is partially constructed from repurposed materials. Notably the wooden frame offered a new life to broken bed slats rescued from city skips. On disassembly, the salvageable electronic components of the system will be reused in future projects and the wooden frame will return to the first author's reclaimed wood collection.

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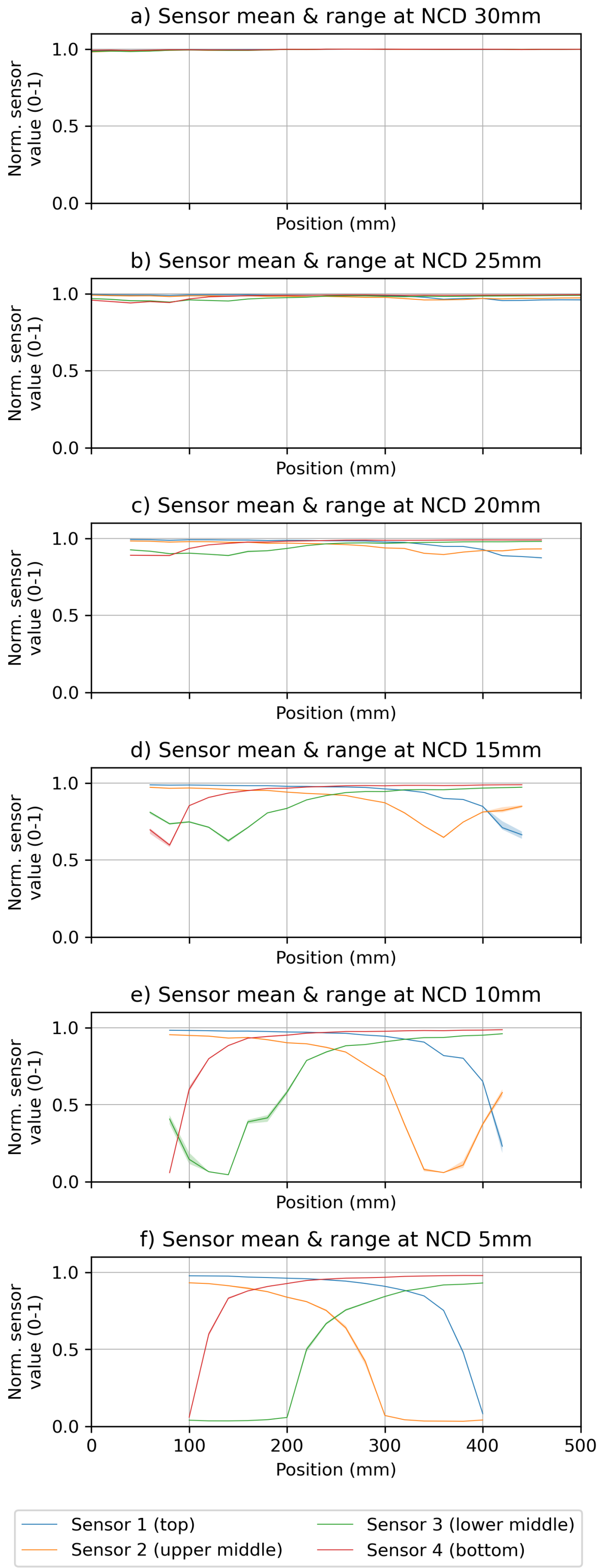

Figure 6: The normalised sensor values recorded in the dataset at each neck-cord distance (NCD), across the cord length. Lines denote the mean of all examples at a given displacement and position, while the shaded areas denote the range of sensor readings at that combination. Note in a) and b) that the NCD was recorded across the entire cord length, whereas smaller NCD values in c) to f) were not recorded at the extremities of the cord due to the cord tension. Some combinations are also not bijective, particularly at low displacement/high NCD values, which explains why the model is less accurate at high NCD values and towards the ends of the cords.

Figure 7: The copper capacitive strips on the back of the neck, facing towards the performer.

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