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TOWARDS UNDERSTANDING THE INFLUENCE OF MASS DISTRIBUTION ON THE PERCEIVED WEIGHT AND FORCE CONTROLLABILITY OF A VIOLIN BOW

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ABSTRACT

For bowed string players, the bow becomes a natural prolongation of the musician's arm, and its ability to be controlled is therefore really important. Appreciations like "it is quite light" or "the weight is not even" are common among violinists, and reveal differences between bows on the perceived weight at different bow-string contact points (frog, middle, tip). The present study aims at exploring how bow mass distribution influences its perceived weight and behaviour in different playing conditions.

The mass distribution of a light violin bow built specifically for this project is changed by adding masses at different parts of its stick. The influence of mass distribution on the mechanical behaviour of the bow in a playing situation is explored, mainly through the variation of both center of gravity and moment of inertia. Then, different mass distributions on the same bow are tested by professional musicians, and some perceptual tests are conducted. Their evaluations will be correlated with the finger forces required to maintain a given force on the string and the bouncing frequency of the bow.

Keywords: *violin bow, perception, mechanics, bow making, human-instrument interaction.*

1. INTRODUCTION

Bows mainly consist of two parts (Fig. 1): the hair that is in contact with the strings, traditionally made of horsehair to which rosin is applied to increase its adherence; and a wooden stick whose main function is to maintain the tension of the hair, traditionally made of pernambuco wood. In this study, we focus on the latter. When playing, violinists hold the bow with their right hand and control the main bowing parameters: speed, position and vertical force on the string. Different parameters trigger different vibratory regimes of the string, which are transmitted through the bridge to the sound box and finally to the air, resulting in different sounds (see [1]). Fiddlers learn to control bowing parameters to produce the sound they want following their interpretative will.

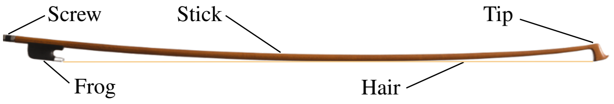

Figure 1. Overview of the violin bow main parts.

Despite being an essential element for the musician, the bow has not been studied as thoroughly as the violin until the end of the twentieth century. Concerning the musicians' perception of bows, only a few studies have been conducted. One of the first attempts to unveil how bow mechanical properties are linked with its perceived qualities was conducted by Bissinger in 1995 [2]. He did modal analysis and bounce tests of eight violin bows and had them tested by an expert violinist. The bow with

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highest modal damping was perceived as "squishy, soft," whereas the least damped were perceived as with "out-of-control feeling to *spiccato* and *ricochet*." [1] Those classed as being "excellent *spiccato* bows" had damping values in between. A few years later, Caussé et al. [3] conducted a dissimilarity test on twelve expert violinists with a set of seven carbon fiber composite bows and a pernambuco bow. They could not correlate quality criteria with physical properties like mass, center of gravity, stiffness or hair tension. However, they identified three important bow playing properties among all violinists: balance, flexibility and responsiveness. Ablitzer [4] explored the influence of camber (i.e. the curve of the stick) on the playing qualities of the bow during his PhD. He used three bows with different camber, which he characterized and were tested by two expert violinists. He remarked that violinists tend to adjust hair tension based on the hair-stick distance, and make finer adjustments after playing with this initial tension. The variations on hair tension – determined by camber for a given hair-stick distance – influenced the perceived attack transients (consonant sounds) and reactivity of the bow, as well as the timbre of the sound. Bow maker Joseph Regh published recently the result of a lifetime's study of the bow [5]. For years, he asked professional violinists to play and rate a set of 75 bows of varying quality with measured physical properties. Three properties stood out as determining the perceived bow quality: moment of inertia, total mass and stick stiffness. For all three, the higher they were, the better the bow was rated.

None of the works cited above focused on how mass distribution influences bow quality. In addition, most of them used different bows with their own characteristics (wood, hair, mass distribution or total weight). Their respective influences on the perceived qualities are hard to uncouple. In 2017, an experiment was conducted at the University of Montreal under the direction of Aurélie Tomezzoli [6] on the influence of bow camber but also its mass distribution on violinists' preferences. In this experiment, a single 62 g bow was used, and different masses were added at different locations (tip and frog, +1 and/or +2 g). In general, the masses added at the tip and/or frog had a negative impact on musicians' ratings, which could be caused by big changes in bow mechanical properties as the center of mass and the moment of inertia. Furthermore, in the case of adding +2 g to the tip and frog, the total weight would be closer to the standard weight of a viola bow (70 g) than that of a violin bow (60 g) [7], quite far from what violinists are used to play with.

The present study adopts a similar approach as that of [6]. Using one single bow that has been built as light as possible, we try to find how different mass distributions are perceived by musicians by adding masses along the stick. The tested bow weighs around 60 g – the standard for violin bows [7] – for any configuration of the added masses. This allows for test conditions closer to those a violinist would encounter when trying out different bows.

2. STATIC FORCE CONTROLLABILITY

This section was inspired by the work of Askenfelt on finger touch sensation in stringed instrument playing [8]. When playing the violin's low-pitched strings (G and D) the bow is drawn horizontally. Its weight has to be compensated by the musician in order to press the string with the desired force, mainly with both index and little fingers depending on the bow-string contact point. As will be shown, the position of the center of gravity – given by mass distribution – influences the necessary finger forces that control the vertical pressure on the string.

The bow can be modeled as if moving along an axis perpendicular to the string. In a playing situation bow kinematics are way more complex and rich (see [9]), but it is a good first approximation to picture how violinists control vertical force on the string. Let us also consider that its movement is restricted to a plane perpendicular to the direction of gravity, like when playing on the G string, and that it does not rotate around any axis. Hence, the only forces acting on the bow are its weight, the restoring force of the string and the musician's control forces, applied by thumb, index and little fingers (Fig. 2).

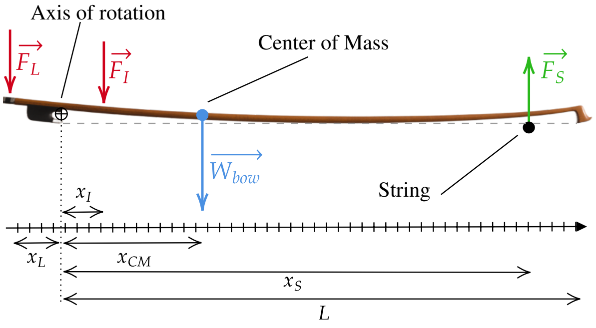

Figure 2. Forces on the bow and distances to the pivot point.

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[1] *Spiccato* and *ricochet* are bow strokes (bowing techniques) involving notes played with a bouncing bow.

Index F_I and little F_L finger forces are defined positive and parallel to the direction of gravity, which is also positive. From rotational equilibrium on a pivot placed at the thumb position, it is then possible to infer the formula of F_I and F_L as an expression of its total weight W_{bow}, the restoring force of the string on the hair F_S – which is negative – and the distances between the pivot and the center of mass x_{CM}, little x_L and index x_I fingers:

$$\begin{cases} F_I = \frac{F_S}{x_I}x_S - W_{bow}\frac{x_{CM}}{x_I} & x_{eq} \le x_S < L \\ F_L = -\frac{F_S}{x_L}x_S + W_{bow}\frac{x_{CM}}{x_L} & 0 < x_S \le x_{eq} \end{cases} \tag{1}$$

Where $x_{eq} = x_{CM}W_{bow}/F_S$ represents the position of the bow on the string where violinists should stop pressing with the little finger and start pushing with the index on a down-bow stroke (vice versa for an up-bow stroke) in order to obtain an homogeneous force on the string. At this point x_{eq}, no finger force is required to have a force equal to F_S on the string, and it depends on the position of the center of mass of the bow and thus on its mass distribution. In the case of higher pitched strings (A and E), bow motion happens in a direction very close to the direction of gravity. When playing on these, the contribution of bow's weight to string force is insignificant, and thus bow mass distribution would not have an impact on the required finger forces to press the string.

In Fig. 3 an example of this forces for a given bow is shown. Experimental validation was made with a setup consisting on a force sensor placed on the little or index finger positions respectively (Fig. 4). A mass of 101 g was attached to one end of a light wire hanging from a pulley, while the other was tied to the bow at different x_S positions, giving a constant vertical force of about 1 N. The pivot position was fixed with a metallic hook.

The moment of weight, i.e. the product of the bow's weight W_{bow} times the distance from the pivot axis to its center of gravity x_{CM}, determines the range of finger forces. For the same weight, a bow with the center of gravity closer to the tip would reduce the index finger force necessary to trigger a vibratory regime. On the other side, playing at the frog would require greater little finger force to compensate bow's weight than in the case of a center of gravity closer to the frog. The perfect bow should have the center of gravity placed in such a position that the violinist feels comfortable playing anywhere from the frog to the tip.

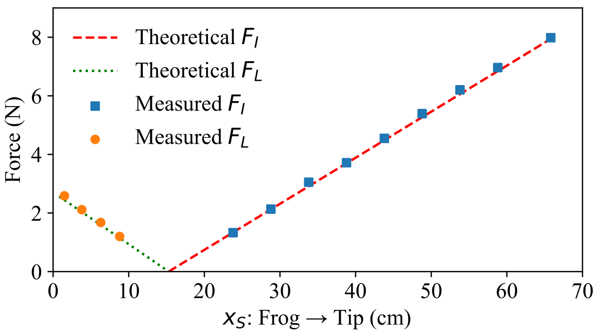

Figure 3. Theoretical – Eq. (1) – and measured right-hand finger forces against bow-string contact position, for a constant vertical string force F_S of about 1 N. Error bars are smaller than symbol size. Bow properties: $x_{CM} = 29.6$ cm, $W_{bow} = 66$ g. Finger distances to pivot: $x_I = 6.3$ cm, $x_L = 5.6$ cm.

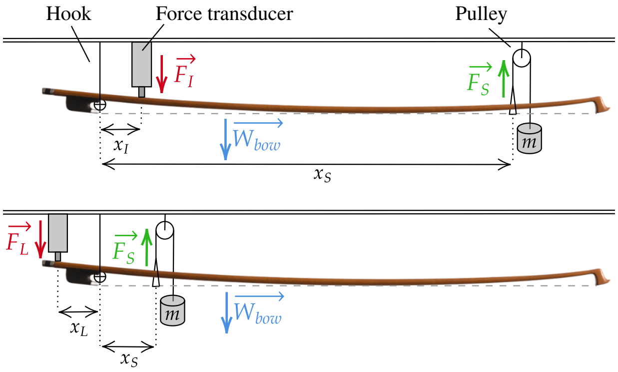

Figure 4. Setup for measuring static finger forces. Top: index finger (Fig. 3, squares). Bottom: little finger (id., circles).

3. BOUNCING BOW

Some classical bow strokes like *spiccato* or *ricochet* involve a bouncing motion of the bow on the string. This behavior has been described thoroughly by Askenfelt and Guettler [10–12]. The first mode of vibration of the bow on the string is known as the bouncing mode. Askenfelt [10] proposed a rigid stick, quasi-static bow model to obtain the bouncing frequency, which is replicated hereinafter.

When the hair of the bow is in contact with the string, it bends approximately in a shape similar to a triangle. In

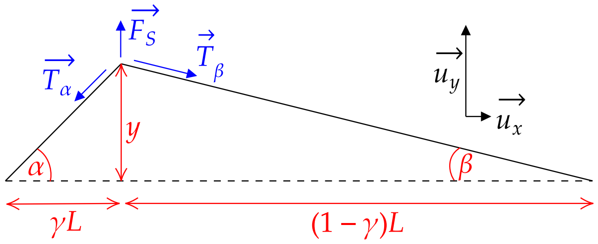

Figure 5. Shape and forces on the loaded bow hair.

Fig. 5 this shape of the loaded hair is represented with the main forces that take part in this deformation (scale of y-axis is much smaller than scale of x-axis). Through some simplifications, it is possible to obtain an expression of the restoring force that acts to bring the hair to its equilibrium position (dashed line in Fig. 5). First, let us apply Newton's second law to the loading point of the hair, which is in translational equilibrium:

$$\overrightarrow{F_S} + \overrightarrow{T_\alpha} + \overrightarrow{T_\beta} = 0 \tag{2}$$

For this particular problem, let us assume that the point of contact between the hair and the string is frictionless. In that case, tension is constant along hair length and we have $|\overrightarrow{T_\alpha}| = |\overrightarrow{T_\beta}| = T$. Projecting Newton's second law onto the y-axis gives then:

$$F_S - T\left(\sin\alpha + \sin\beta\right) = 0 \tag{3}$$

From Fig. 5 we can obtain both tangents of α and β angles. Small-angle approximation ($\sin x \approx \tan x$) simplifies the restoring force F_S formula:

$$F_S \approx \frac{T}{(1-\gamma)\,\gamma L}\, y \tag{4}$$

where $T\left[(1-\gamma)\,\gamma L\right]^{-1}$ is the equivalent stiffness of the hair for an in-plane vertical displacement y. Let us suppose that the bow can rotate around an axis at $\gamma = 0$, perpendicular to the x-y plane. Let us assume that the only force that acts on the system is the restoring force $\overrightarrow{F_S}$. The application of the rotational analog to Newton's second law using small-angle approximations leads us to the following equation of motion:

$$\ddot{y} + \frac{T\gamma L}{(1-\gamma)I}\, y = 0 \tag{5}$$

This equation describes the motion of a simple harmonic rotating oscillator, characterized by its natural angular frequency $\omega_{BNC} = 2\pi f_{BNC}$. This bouncing (BNC) frequency depends on the tension of the hair T, the position of the loading point along the x-axis γ and the rotational inertia of the bow I:

$$f_{BNC} = \frac{1}{2\pi}\sqrt{\frac{T\gamma L}{(1-\gamma)I}} \tag{6}$$

First described and measured by Askenfelt in 1992 [10], this frequency is valid for on-string motion, i.e. when the bow stays in contact with the string. It takes values between 7 and 30 Hz along the stick, and it depends on the moment of inertia of the bow and thus on its mass distribution. Colin Gough refined this model [13] through modal analysis, showing that Askenfelt model describes the bouncing mode well for positions between the frog and the middle of the bow. For the upper part of the bow, he demonstrated that the bouncing rate is influenced by the lowest frequency vibrational modes of the bow stick.

For off-the-string bowing techniques, the total bouncing period corresponds to the half-period of the on-the-string cycle – Eq. (6) – plus the time it takes the bow to return to the string [13]. This second off-the-string half-period may be controlled by the violinist by exerting a couple on the bow with his or her index and little fingers (see Fig. 2), modifying the net bouncing rate. Moreover, the deflection of the string under the influence of the bow force would also modify the bouncing frequency. Askenfelt [10] estimated a reduction of the bouncing frequency for the violin G string of about 15%.

4. MATERIALS & METHODS

Previous studies [14] have shown that even for a well trained audience, it is almost impossible to differentiate between a violin and a viola bow only from the perceived sound. On the other side, musicians are able to feel the difference between those bows, notably from haptic perception and from playing qualities. Professional violinists seem to not only distinguish a viola bow from a violin bow, but also between two violin bows. With the aim of understanding how musicians perceive changes in the mass distribution of the bow, a series of perceptual tests have been planned with professional violinists using an experimental bow whose mass distribution can be easily modified.

Table 1. Set of bow mass configurations tested by musicians and measured bow mechanical properties. $\{\Delta m_{tip}, \Delta m_{clamp}, \Delta m_{frog}\}$: added masses at the {tip, clamp, frog}. The masses of the clamp, foam and paper hiding the magnets (Fig. 6, bottom) are considered. m_{bow}: bow total mass; x_{CM}: distance from the center of mass to the pivot point (beginning of the hair at the frog); I: moment of inertia with respect to the pivot point; $\{\Delta x_{CM}, \Delta I\}$: variation of mechanical properties with respect to the reference bow A in percentages.

Bow	Δm_{tip} [g]	Δm_{clamp} [g]	Δm_{frog} [g]	m_{bow} [g]	x_{CM} [cm]	Δx_{CM} [%]	I [$\mathrm{g\,m^2}$]	ΔI [%]
A	0.14	6.88	0.77	60.05	19.5		4.92	
B	0.70	5.27	1.82	59.93	19.6	$+0.5$	5.13	$+4.2$
C	1.75	1.91	4.27	60.15	19.5	0.0	5.49	$+11.6$
D	0.22	4.78	2.87	60.15	18.7	-4.1	4.90	-0.4
E	0.22	1.91	5.74	60.25	17.5	-10.3	4.84	-1.6

4.1 The experimental bow

In April 2023, bow maker Duilio Spalletta[2] made a violin bow specifically for this project. The total mass of the bow, equal to 52.6 g, is significantly lower than the standard (about 60 g). Lightening was possible thanks to the use of low density pernambuco wood for the stick ($0.850\,\mathrm{g\,cm^{-3}}$). Also, the tip plate was removed and the head was carved following a thin model. At the frog, several elements were lightened as well using different materials: titanium screw, round-shaped ebony frog without eye, silver-wound silk winding, kangaroo leather and nickel ferrule and adjuster (see [7] for detailed information on bow making).

The lightness of this bow allows to modify its mass distribution by adding masses along the stick until reaching the standard weight, which gives a margin of about 7 to 8 g. In order to facilitate the task and easily switch from one mass configuration to another, we added small neodymium magnets (0.07 , 0.35 , 0.56 and 1.98 g) on a magnetized nickel clamp (1.67 g). In addition, the nickel screw adjuster at the frog was magnetized to hold the magnets, as well as a thin nickel plate glued at the tip.

4.2 Mass distributions to be tested

Because of their influence on different aspects of controllability (see sections 2 and 3), the two physical properties on which we focus here are the moment of bow's weight and the moment of inertia. In order to explore the influence of each one on the violinist perception separately, we conceived different mass distributions that allowed us to modify one keeping the other constant. The values of added masses and measured centers of mass and moments of inertia are shown in Tab. 1: bow A is the reference bow; bows B and C have different moments of inertia, and the same center of mass; bows D and E have different centers of mass, with the least variations of moment of inertia that we could reach. Top of Fig. 6 shows the detail of the added magnets along the stick. For all configurations, the metallic clamp at the middle of the bow was at the same position (15 cm from the pivot position) to avoid any difference between bows that could be perceived visually. All distributions give values that are into the typical limits of modern violin bows [5].

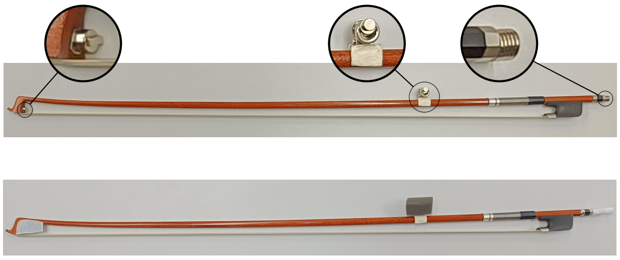

Figure 6. Test bow with added masses. Top: detail of the magnets (bow B of Tab. 1). Bottom: bow as seen by participants, with paper covering tip and frog magnets, and a light piece of foam covering the magnetic clamp.

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4.3 Measurement of bow mechanical properties

Bow mass was measured with a precision balance. The centers of mass were determined through empirical estimation using a narrow square piece measuring $2\,\mathrm{mm}$ in width: the stick was carefully positioned on this piece until the point of balance was achieved. The moment of inertia was determined by suspending the bow from the pivot point (the axis of rotation shown in Fig. 2) and allowing it to oscillate freely. The motion of this physical pendulum can be described using Newton's second law for rotation, which results in a period equal to:

$$T = 2\pi\sqrt{\frac{I}{m_{bow} g x_{CM}}} \tag{7}$$

The moment of inertia about the bow's point of suspension is subsequently calculated from the oscillating period and the measured values of the bow's mass and center of mass position. Hair tension was determined by measuring its deflection after applying a mass of $50\,\mathrm{g}$ at the midpoint of its total length, following the methodology described by Regh [5].

4.4 Protocol of the perceptual tests

The different mass distributions described in Tab. 1 are tested by musicians in two different tasks: discrimination and constrained playing tests. Six professional violinists (42.2 $\pm$ 9.9 years of experience) and two students (13.0 $\pm$ 1.0 years of experience) participated in the test. All of them were trained in the Franco-Belgian violin school, or had it as an important influence. The study was reviewed and approved by the Ethics Committee of Sorbonne University (`CER-2023_SALVADOR_CASTRILLO_ARCHET`).

One participant did not complete the last test due to lack of time. At the beginning of the session, players were asked to adjust the hair tension of bow A according to their personal preference while their own bow properties were being measured. Subsequently, the hair tension of bow A was recorded prior to the test, and participants were instructed not to make any further adjustments to it during the session. Visual cognitive biases were avoided by hiding magnets with light pieces of paper and foam (Fig. 6, bottom).

4.4.1 Discrimination test

To explore to what extent musicians are able to perceive little (bows A-B, A-D) or big (bows A-C, A-E) changes on both center of mass position and moment of inertia, a same-different test is performed. For each trial, the violinist was asked to play with two presented bows and to indicate if they were different or not. They were also encouraged to verbalize comments on what they perceive as soon as they pick up the bow. First was always bow A, presented as the reference bow, while the second was any of the bows of the set presented in Tab. 1 (A-X, where X $\in \{$A, B, C, D, E$\}$).

Each participant performed six trials. All five bows from A to E were tested by each judge, and one of them was repeated randomly. The order of presentation of the bows was also random.

4.4.2 Constrained playing test

A semantic classification of the verbalized comments given by participants could allow to perceptually characterize each mass distribution, as has also been done before for the acoustic qualities of different violins (Bilbao Project [15, 16]). To analyze how musicians describe big changes in bow properties when playing, we asked them to evaluate the pairs A-C (big change in moment of inertia) and A-E (big change in center of mass position):

- **Bows A-C**: all-string scale in *spiccato* (2 octave G major, first position), *ricochet* (note A on G string and on E string, first position), 4-string *ricochet* (G major chord, first position). For *spiccato* and *ricochet*, they were asked to play in tempo with a metronome that was set to the same rhythm for both bows.
- **Bows A-E**: on the G string, one-string *détaché* scale (A major) played at the frog and at the tip in *forte*. Here the metronome was also used.

After each constrained test, they were allowed to play freely in *spiccato* (A-C) and *legato* on the G string (A-E) in order to give a complete evaluation.

5. RESULTS AND DISCUSSION

The average values for the measured properties of the bows from the eight participants in the test are as follows: bow mass $m_{\text{bow}} = (61.21 \pm 2.00)\,\mathrm{g}$, center of mass position $x_{\text{CM}} = (18.6 \pm 0.9)\,\mathrm{cm}$, and moment of inertia $I = (5.12 \pm 0.37)\,\mathrm{g\,m^2}$. The average bow mass is $1.21\,\mathrm{g}$ higher than the standard value of $60\,\mathrm{g}$, which represents a variation of only 2%. The average center of mass position and moment of inertia values validate the choices made during the design of this experiment, as shown in Table 1, as they fall within the typical ranges for the participants' bows.

Bow B had the closest moment of inertia to the average of those owned by the participants. On the other hand, when considering the bow moment of weight (bow mass multiplied by the center of mass position), bow D was the closest to the average. Regarding hair tension, the average tension for bow A was $(46.4 \pm 1.8)\,\mathrm{N}$, whereas with their own bows, the average tension was $(41.2 \pm 5.1)\,\mathrm{N}$. Participants showed greater consistency in hair tension when using bow A compared to the tension chosen for their own bows. This observation is in line with Ablitzer's findings [4], which suggest that musicians typically select hair tension based on the hair-stick distance initially and then make minor adjustments.

5.1 Discrimination test

The percentage of responses "different" to the same-different test are given in Tab. 2. These results indicate that, based on the protocol described in Section 4.4.1, participants were unable to discriminate when the second bow was identical to the first more of half of the time.

Table 2. Proportion of responses "different" to the same-different test. First bow was always bow A.

Second bow				
A	B	C	D	E
70%	90%	70%	56%	89%

5.2 Constrained playing test

In the test of the bows with contrasting moment of inertia, two violinists clearly expressed a preference for bow C over bow A when playing *spiccato* or *ricochet*. They described it as "vigorous (*nerveux*)", "reactive (*réactif*)" or "precise (*précis*)". On the other hand, five violinists did not like bow C, with four of them stating that it produces excessive bouncing and is challenging to control compared to bow A. One violinist was unsure about their preferred bow. Interestingly, the moments of inertia of the bows owned by the two violinists who favored bow C over bow A were not particularly close to the moment of inertia of bow C (5.05 and $5.14\,\mathrm{g\,m^2}$). Overall, all participants noticed a significant change when the moment of inertia was dramatically altered. The majority of them encountered difficulties in controlling the bow, although they exhibited less consistency in describing this modification.

Regarding the test of different center of mass positions, one of the participants was unable to participate due to time constraints. Out of the remaining seven participants, six of them perceived bow E as lighter than bow A. Lightness was the most prominent quality verbalized by the participants in relation to both bows; however, their preferences varied. Two participants preferred bow A when playing at the tip, while the other five preferred bow E. At the frog, four participants favored bow A over bow E, two of them were uncertain about their preference, and only one clearly preferred bow E. Notably, this last violinist consistently preferred bow E in both tests and possessed a bow with a center of mass closest to the frog among all participants ($x_{CM} = 16.65\,\mathrm{cm}$).

Across all evaluations, the vocabulary employed to articulate playability factors encompassed the quality of attacks, stability throughout the stroke, awareness of different bow parts (notably the tip) and controllability. However, in both tests, participants also evoked various sound qualities such as roundness or clarity.

6. CONCLUSION AND PERSPECTIVES

In this paper, we presented a preliminary study aimed at investigating how violinists perceive different bow mass distributions. By utilizing a lightweight bow, we were able to create five distinct mass distributions by adding small masses while maintaining a consistent total mass across all cases. The resulting mechanical properties of the bows, specifically the moment of inertia and center of mass position, were observed to fall within the typical ranges found in the bows owned by the participating violinists.

A same-different discrimination test was conducted to assess the extent to which violinists perceive changes in moment of inertia and center of mass position. No measure of confidence was recorded regarding their responses. Regrettably, the results of this test were not satisfactory: most participants were unable to detect when the second bow was identical to the first one.

In addition, a constrained playing test was conducted, in which participants were aware that the first and second bows presented to them were different. The task consisted in describing the changes that they perceive, if any. Participants showed little consistency among them when evaluating big changes in moment of inertia. On the other side, the consistency of participants on the perceived change of lightness suggest potential correlations between this quality and the position of the center of mass. This relationship is linked to the range of finger forces required by the right hand to control the bow stick effectively. This raises questions about the results of the discrimination test: when violinists were aware of a change, they expressed very similar descriptions of that change.

Based on this circumstance, several attempts have been made to choose a more effective protocol for the discrimination test. The decision strategy for the same-different test turned out to be psychologically intricate: musicians often detect even the slightest difference between bows and tend to conclude that the bows are different. This phenomenon can be attributed to the complexity of bow quality evaluation, which involves considering multiple sensory aspects including auditory and kinesthetic perception. We finally chose to perform a dual-reference Duo-Trio test, with the reference at First and Middle positions (DTFM): A-X-A-Y where X or Y are equal to A and X is different from Y. The cognitive strategy for this discrimination test is less demanding since the reference bow is presented twice, and the participant has to choose which of the bows X or Y is the reference. This has already been confirmed by three musicians who performed both type of tests. Additionally, a level of confidence in their answers, ranging from 1 (not sure at all) to 5 (very sure), will be collected.

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