Bow-side kinematics studies in violinists: an experimental design tracking intra-/inter-musician variability by bow stroke's type, string played and tempo

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Abstract

Comparison of bow-side kinematics in violinists is hindered by the scarcity of studies available. This makes meta-analysis impossible. This paper assesses the effect of music-based variables (bow stroke, *tempo* and string played) on intra- and inter-participant variability in joint kinematics. The joint kinematics of nine high-level violinists were acquired via a motion capture system while they played a standardized piece of music involving contrasting bow strokes and strings at different *tempi*. Results were compared using linear mixed models using the Root Mean Square (RMS) for each joint. We found highly individualized patterns of play, deduced from a low intra- but high inter-musician variability (4.2° vs. 13.1° of normalized RMS) in joint kinematics. String played and bow stroke had the greatest effect on joint kinematics. The string played had the greatest impact on shoulder kinematics and the bow stroke had the greatest impact on elbow and wrist kinematics. Based on these results, we

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propose guidelines for future research designed to study bow kinematics in the field of biomechanics of violin movements. For ease of comparison between studies and to limit the time and resources required, our main suggestions are to use repeated measures designs with a *legato* reference condition and to choose pieces of music spanning multiple strings.

Keywords: Biomechanics, Experimental design, Kinematic variability, Violin

1 Introduction

More than three quarters of musicians will suffer from playing-related musculoskeletal disorders (PRMD) over the course of their career. Bowed-string instrumentalists are especially at risk of upper limb injuries [(1)]. String players suffer a higher rate of injuries than the general musician population (e.g. 9.7 versus 8.3 injuries per 100 people per year [(2)]). The right shoulder (i.e., the bow side) is affected in 37.1%, 31.3%, 31.8%, and 40.0% of violinists, violists, cellists, and double bassists, respectively [(3)]. Since injuries may compromise the career of these musicians, investigating the causes of PRMD is important. The literature highlights several risk factors like musician age, gender, and the instrument played [(3–5)]. Moreover, most epidemiological studies are performed using questionnaires. While questionnaires may provide insights into PRMD occurrence, they do not enable inferences about the actual pathomechanisms involved. Biomechanical analyses can be expected to shed light on these injuries.

In a scoping review of the biomechanics of bowed string musicians [(6)], 25 out of 34 studies focused solely on violinists, nine addressing the bow arm (i.e., right). One study [(7)] simultaneously investigated kinematics and muscle activity. Another study [(8)] solely explored muscular activation. Of the eight joint kinematic studies, four reported the right upper limb kinematics describing only one degree of freedom per joint [(9–12)]. This seems inappropriate, given that the shoulder is usually described as a ball-and-socket joint with 3 degrees of freedom [1] (DoF) and that the elbow and wrist are usually described as constrained ball-and-socket joints (2 DoF) [(13)]. Only three studies [(14–16)] reported the full 3D kinematics. A recent kinematics study focused solely on the scapulothoracic

[1]A glossary of biomechanical and musical terminology is provided in Section 7 to help readers without backgrounds in these fields. A star (*) was added at the first occurrence of each word that appears in the glossary.

joint[17]. This small number of studies on the kinematics of the bow arm of violinists limits the generalizability of their results.

The instrument played influences the type of injuries that a particular musician is likely to develop[3]. This suggests that instrument design and technique ergonomics influence kinematics and muscular loads. The bow stroke* itself affects violinists' upper limb kinematics. For example, the kinematics involved in a *spiccato** bow stroke differ from those of a *legato** bow stroke[14,15]. Music-based variables (e.g. nuance*, *tempo**, bow stroke* and strings played [low (G and D) or high (A and E)]) probably all produce their own specific effects. However, studies commonly assess the effect of only one or two of these variables simultaneously. For instance, violinists are asked to play different strings with one bow stroke: *legato*[14,18] or *spiccato*[15]; or to play different strings at different *tempi*[7,14]. Additionally, from a joint kinematics point of view, it is not known whether these variables interact during playing. This is of importance, because interactions between variables limit interpretation of the results. In one literature review on musculoskeletal injuries in bow musicians[19], the conclusion was that "to obtain more significant study results, studies with higher methodological quality including sample size, homogeneous study protocol, and similar study populations are suggested". In order to provide a more solid grounding for the biomechanics of music literature for violinists, higher quality assessment of kinematics needs to be performed.

The aims of this research were: 1) to assess the repeatability of the kinematic strategies involved in playing and their commonality among violinists; 2) to investigate the effect of musical performance variables of violinists (i.e., bow stroke, speed of play, and string played); and 3) to integrate the findings into recommendations for future research allowing finer comparison of violinists' kinematics. Due to the inherent changes in motion required to differentiate between the musical variables, it was hypothesized that each performance variable (bow stroke, speed of play and string played) would influence joint kinematics. Conversely, given that researchers currently pool results to analyze them, we also hypothesized that both intra- and inter-kinematic variability would remain sufficiently small to allow for using randomized control group designs in future studies.

2 Materials and Methods

2.1 Experimental procedures

After giving their informed consent (Ethics 17-018-CERES-D, Université de Montréal), 9 expert violinists (8 females and 1 male; mean(std): 28(7) years old, 59(8) kg, 161(5) cm, 21(9 years of experience) were equipped with 45 skin markers (Figure 1) on their right upper limb. To personalize the multibody kinematic chain model, the participants maintained both an anatomical and a relaxed pose, and performed functional setup trials [20]. The setup trials consisted of large rotations and arc movements in all directions to maximize the rotations along all degrees of freedom (DoF) between two adjacent segments. Due to the length of the experiment, the setup trials (usually performed at the beginning of a session) were performed during bow-shape modifications (detailed below). Throughout the experiment, skin-marker trajectories were collected at 100 Hz using an 18-camera Vicon™ motion capture system (Oxford Metrics Ltd. Oxford, UK).

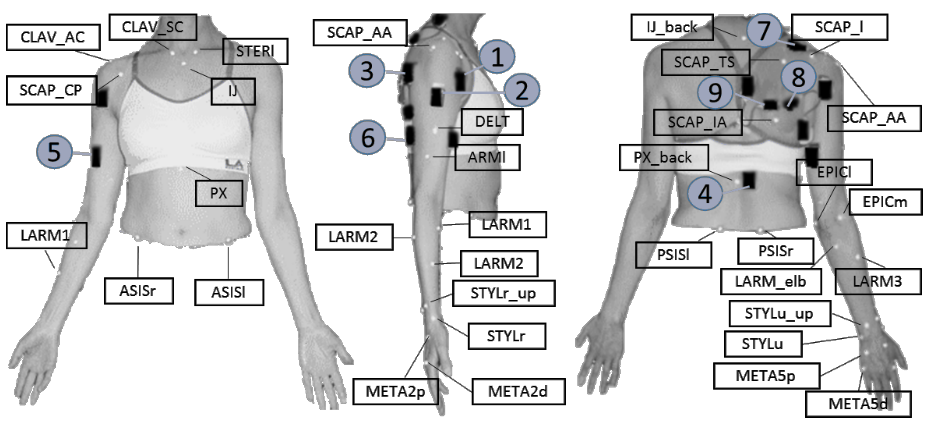

Figure 1: A total of 45 markers based on Jackson et al. [20] were glued to the skin alongside electromyography units (data not used in the present study).

The violinists played a standardized piece (S2M Lab Theme / A research music) specifically written for the study (Figure 3). The score* was constructed from a melody of four bars* played as follows: *legato* (lines 1-3) and *spiccato* (lines 2-4) played on the low strings (G/D strings, lines 1-2) and on the high strings (A/E strings, lines 3-4). The data from the remaining two lines of the score were not used for this study. Figure 2 shows the bow arm position while playing on the low or high strings from the frog to the tip of the bow. The whole piece was played at two different *tempi*, namely 60 and 120 beats-per-minute, for a total of 74 s and 37 s respectively. The musicians had free choice of fingering* and could practice the piece as much as needed before the beginning of the experiment. To keep track of the beats, participants wore a headset on one ear so they could hear a metronome set at the proper speed. All trials started and finished in the anatomical pose while holding the bow and the violin with their respective normal hand (the bow on the right and the violin on the left). After the trial started, participants were asked to bring the bow to the frog* (the end near the hand) on the G-string (the lowest violin string), and thereafter were free to start playing when ready.

Figure 2: Position of the bow arm while playing on a low (G) string (top) and on a high (E) string (bottom) from the frog to the tip (left to right) of the bow.

All but one of the violinists played their own violin; one participant being provided with a violin. All participants used the same modified bow (62 g). This protocol was part of a larger project [2] where the shape and the mass of the bow

[2]This paragraph describes details of the overall project protocol which may be relevant to the upper limb kinematics of the musicians. A short video depicting the larger experiment can be accessed by following this link `https://youtu.be/T-kwoHz1FEc`.

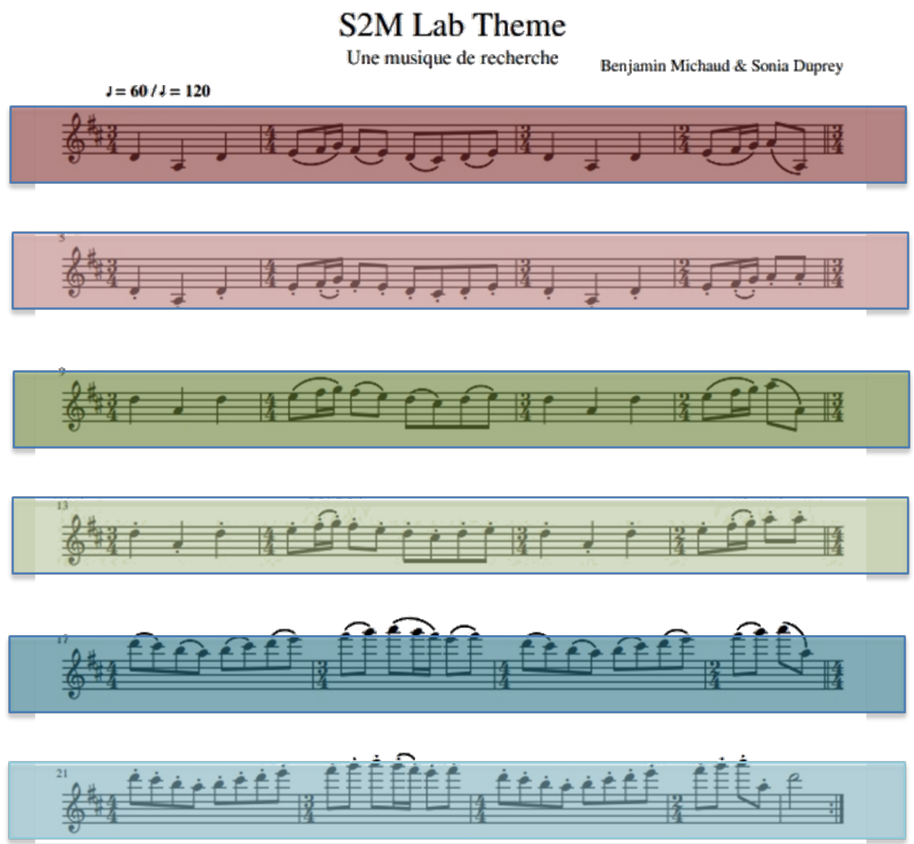

Figure 3: Score of the music composed for the study. The piece includes *legato* (odd lines) and *spiccato* (even lines) sections played on the G/D strings (shades of red) and on the A/E strings (shades of green). The piece is played at 60 and 120 beats-per-minute.

were modified between each rendering of the piece. The modifications to the bow consisted of three bow cambers* and six permutations of three 1 g masses glued to the frog (0 or 1 g) and/or to the tip* (0 , 1 or 2 g) (Table 1), generating a total of 18 different configurations. The different masses were configured to mimic normal modifications that might be made by a bow maker trying to change the bow's behavior during the normal course of practice. The three cambers of the bow were normal-style (maximum curvature at mid-point), baroque-style (maximum curvature near the tip, the end farthest from the hand), and cello-style (maximum curvature near the frog). The bow modifications (which took about 20 min each) were performed by a bow maker during the experiment.

The six bow-mass and two *tempi* conditions were block-randomized inside a camber configuration, and the three camber configurations were randomized among participants. This gave a total of 36 repetitions of the piece by each violinist, covering all the permutations of the three experimental configurations: three bow cambers, six bow masses and two *tempi*. Preliminary results from all the configurations showed that joint angles for all but one participant were not significantly affected by either the shape or the mass of the modified bow (based on 1D statistical parametric mapping ANOVA [21]). The data from this one participant who differed from the others were therefore removed from the analysis. The bow-camber and bow-mass data from the other participants were pooled and treated as trial repetitions. The protocol also included surface and indwelling electromyography data acquisition on the right shoulder and arm; these data, however, are not reported here.

Table 1: All permutations of masses added to the bow.

Permutation	Frog	Tip
1	0 g	0 g
2	1 g	0 g
3	0 g	1 g
4	1 g	1 g
5	0 g	2 g
6	1 g	2 g

2.2 Data processing

A personalized 6-joint and 18-DoF kinematic chain* of the upper limb, consisting of the pelvothoracic (6 DoF), the sternoclavicular (2 DoF), the acromioclavicular* (3 DoF), the glenohumeral* (3 DoF), the elbow (2 DoF) and the wrist (2 DoF), was constructed for each participant. The pelvothoracic and wrist joint centers and the elbow axes of rotation (flexion-extension and pro-supination) were estimated using the SCoRE and SARA algorithms [22,23], respectively, from the setup movements. The other joint centers were located using anatomical or predictive methods as recommended by Michaud et al. [24]. A scapulothoracic gliding kinematic constraint was also added to the kinematic chain. It was defined by a point in the middle of the scapula that must remain in contact with an ellipsoid fitted on the thorax [25]. The relaxed posture was used as reference pose, that is the position where all the angles are defined as zero.

The joint kinematics were reconstructed using an extended Kalman filter [26] implemented in the Biorbd biomechanical toolbox [27].

For all the trials, in accordance with the International Society of Biomechanics (ISB) recommendations on the upper limb [28], the joint angle time histories of the thoracohumeral* (namely elevation plane, elevation, and axial rotation), the elbow (namely flexion and supination) and the wrist (namely flexion and ulnar deviation) were extracted. The thoracohumeral joint angles were obtained from the homogenous transformation matrix between the thorax and the humerus, while the others were directly taken from the model output. An automatic algorithm was used to cut the trials from the beginning of the first down-bow* to the end of the last down-bow of the piece. The trials were thereafter time-normalized and cut into four sections—namely low-strings *legato*, low-strings *spiccato*, high-strings *legato* and high-strings *spiccato*—each corresponding to a different line of the score. The automatic cut and classification were visually validated by superimposing the data and manually adjusted when necessary. Finally, from the time-normalized data, the integral of each DoF was calculated for each section, using the trapezoidal rule to obtain the normalized integral. Since the normalized integral encapsulates all the playing technique kinematics data in a single value, time-independent statistics could be used to easily and comprehensively compare the results. As stated earlier, the camber and mass data were pooled and considered as repetitions of the same conditions.

2.3 Statistics

For each DoF, Intra- and inter-participant kinematics variability was assessed by computing, the mean standard deviation of all trials per participant. All trials of all participants were pooled for the integral values.

Due to the repeated measures scheme derived from pooling the shape and mass configurations and due to the large discrepancies between intra- and inter-participant kinematic variability, linear mixed models were used to compare experimental conditions. Overall, seven linear mixed models (one for each DoF) were constructed using the open-source statistical analysis software JASP (Version 0.14, University of Amsterdam) to investigate the effects of the conditions on the normalized integral. The fixed effect variables were the *tempi* (120 vs. 60 bmp), the bow strokes (*legato* vs. *spiccato*), and the strings played (low strings vs. high strings). The random effects grouping factors were the participants.

The alpha threshold was set to 0.05 and Bonferroni corrections were used for the post-hoc analyses. The methods used for the kinematic data analyses and the statistics were chosen after discussions with expert groups in each field.

3 Results

Intra-participant kinematic variability was about three times lower than inter-participant kinematic variability (Table 2). Moreover, each participant showed distinctive patterns of movement in each condition (Figure 4).

Table 2: Mean intra-participant variability and inter-participant variability for all DoF

Joint	DoF	Mean intra-participant variability (°)	Inter-participant variability (°)
Shoulder	Elevation plane	5.3	15.4
Shoulder	Elevation	2.8	9.2
Shoulder	Axial rotation	2.8	11.4
Elbow	Flexion	4.2	12.2
Elbow	Supination	4.0	14.7
Wrist	Wrist flexion	5.7	16.4
Wrist	Ulnar deviation	4.5	12.3
Mean	4.2	13.1	

The linear mixed models did not reveal any triple interactions for any DoF. Significant double interactions were found between string played and bow stroke for elevation plane ($p = 0.021$), elevation ($p < 0.001$), and supination ($p = 0.008$). Main effects revealed that velocity had no significant effect on any DoF. In contrast, string played and bow stroke had a significant effect on several DoF (Figure 5).

4 Discussion

The goal of this study was to provide experimental evidence regarding the bow-side kinematics of violinists. The main findings were: 1) the distinctive nature of violinists' kinematics strategy and 2) a significant effect of string played and bow stroke on joint kinematics. The first hypothesis was that the performance variables (bow stroke, *tempo* and string played) would have an effect on the joint kinematics. This was true for all but one variable (the *tempo*). The second

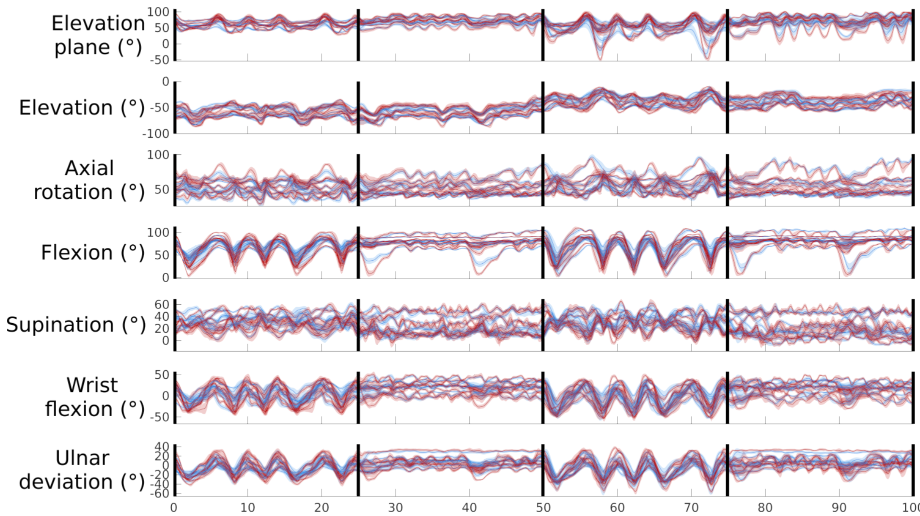

Figure 4: Normalized joint-angle time history for all DoF. The vertical bar delimits the conditions of the piece. Section one ($0-25\%$), two ($25-50\%$), three ($50-75\%$), four ($75-100\%$) are *legato* low strings, *spiccato* low strings, *legato* high strings, *spiccato* high strings, respectively.

hypothesis was that the intra- and inter- kinematic variability would remain in a range that allows for randomized control group research designs. While this was the case for the intra-participant variability, it was not for the inter-participant variability.

4.1 Distinctive joint kinematics strategy

Analysis of individual participants' joint kinematics reveals a pattern followed for each condition by eight out of the nine participants. This means that individual musicians have their own strategies, playing a specific note on a given string at a given velocity using a given bow stroke. While this remains a qualitative analysis of the results, it is supported by the low intra-participant kinematic variability (about 4°) compared to the high inter-participant kinematic variability (about 13°) observed at each joint. As a reminder, this low intra-participant variability was obtained from trials originally designed to induce kinematic variability by changing the shape and the weight of the bow. Major intra-participant variability was found regarding the musicians' appreciation of the bows [29], suggesting that they actually physically felt the difference between conditions. However, a rather small effect, if any, was observed on their kine-

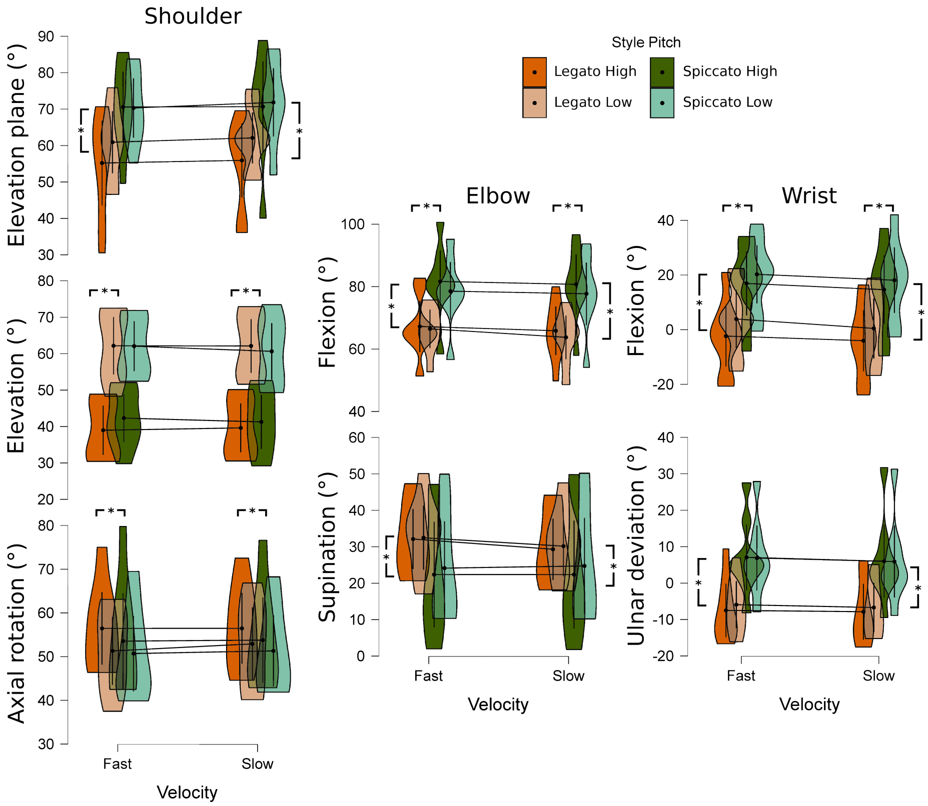

Figure 5: Violin plots of normalized integral of each condition for each DoF. The size of the violin-shaped blobs represents the data sparsity between participants, i.e., wider boxes show low inter-participant kinematic variability, while longer boxes show greater inter-participant variability. Shades of orange and green represent *legato* and *spiccato* bow strokes respectively, while shade strength represents the string played, dark for high strings and light for low strings. The vertical starred bars represent significant differences between bow strokes whereas the horizontal starred bars represent significant differences between strings played.

matics strategy. Ancillao et al. [18] presented a method of acquiring quantitative kinematics data on violinists that was only validated on a single participant. In the light of our results, we suggest that their method should be validated on more participants to enable more generalizable conclusions to be drawn. A single participant is likely to have a specific strategy that applies only to that individual.

Our study does not permit us to conclude on the origin of these distinctive patterns. One hypothesis is that the participants in this study may be representative of multiple schools of instrumental technique. Teacher-student relationships can last a long time in music, and students later become teachers, which means that geographical clusters of technique are likely to emerge. As our violinist cohort came mainly from the Université de Montréal and from Montréal's professional orchestras, which attract musicians from all over the world, their formal educational backgrounds probably involved different clusters of teachers. To validate (or refute) this hypothesis, future studies will need to compare the inter-participant kinematic variability of violinists from the same and from different schools. Another hypothesis is that morphology restricts the choice of strategies on joint kinematics (or strategies the violinist might want to use) if sound quality is to be maintained. This could explain why there was little kinematic variability in conditions that should have fostered it (through modifications to bow shape and mass throughout the experiment). These kinematics restrictions could be problematic in the long term, since repeated movements have been shown to be a major risk factor for overuse syndromes such as tendinitis[(30)].

In any case, to cover most of the techniques and provide findings generalizable to the violinist community at large, our results suggest that a significant number of musicians need to be included in kinematics studies. Moreover, based on the technique cluster hypothesis, reporting participants' principal music school could help provide objective data for future meta-analyses in the field. Finally, to account for the variability of inter-participant kinematics, the experimental design should have participants serve as their own control, for instance, by using repeated measures statistics.

4.2 Velocity, string played, and bow stroke

The effects of velocity, string played, and bow stroke were not consistent across joint angles. The condition that affected the shoulder most was the string played, while the bow stroke affected the elbow and the wrist most. This indicates that multiple bow strokes and strings should be tested in each experiment. In previous studies, authors tended to report kinematics while playing a single *legato* stroke[(9,14)]. Our results suggest that assessing single *legato* strokes only reveals part of the picture, since elbow and wrist joints are highly sensitive to the bow stroke. Thus, changing the stroke can be expected to drastically affect elbow and wrist joint angles. The importance of testing multiple strings is consistent with findings from the study by Mann et al.[31]. These latter researchers concluded that multiple-string scales can be used to estimate muscle activity during violin playing (i.e., that scales on multiple strings are preferable to single-string scales when testing the bow side of violinists).

Due to the closed kinematic chain created by the contact between the violin and the bow, the DoFs can be expected to interact in terms of joint angles. For instance, if during a down-bow the elbow is extended, this is expected to create an outward rotation of the bow (i.e., pointing the bow forward, away from the player). This must be prevented, because the bow must be kept at a 90° angle to the violin and must as far as possible remain at a fixed point on the strings (for instance near the bridge*). To do so, the wrist will extend and the arm will horizontally flex forward. Thus, music-related variables suggest complex interactions between the joints of the upper limb. This is supported by the fact that all the DoF are sensitive to the bow stroke. Unfortunately, the range of cases that can arise from DoF interactions is too great to list them all. We therefore suggest that any joint kinematics study on violinists needs to explore the relevant DoF interdependencies.

The *tempo* did not show any main effects on any of the joints. This contrasts with Shan et al.[15], who reported significant differences in kinematics while playing at different *tempi*. These contrasting results may be explained by the fact that bow velocity is not completely independent of the bow stroke. For instance, increasing the *tempo* should, at some point, force a shortening of the length of the bow used, effectively changing the bow stroke. The fastest condition in our study may still have been too slow to create this effect. In line with our results, we suggest that *tempo* conditions are not required for bow-side kinematics studies as long as a sufficient variety of bow strokes are tested. However, any study addressing joint velocities or accelerations will definitely require a *tempo* condition.

To summarize, in bow-side joint kinematics studies on violinists that focus exclusively on humeral attitude, changing the string played should cover most of the variability. On the other hand, if it is the kinematics of the whole upper limb that are being explored, then researchers should design their experiments to include different bow strokes. In all cases, joint interdependencies should be reported and discussed.

Based on the findings from this study, recommendations for experimental design are proposed, as summarized in Table 3. These recommendations could improve the comparability of research on bowing arm biomechanics in violinists.

4.3 Limitations

There are several limitations to this study. First, it was performed on a convenience sample of a small number of participants. Second, this study used data from a larger study that was not primarily designed to evaluate the sensitivity of the conditions presented here. The larger study was aimed at evaluating sensitivity to a material change that was expected to increase variability in joint kinematics. The results showed a small effect of these material changes on joint kinematics, except for one participant, whose large kinematics differences suggest an actual effect generated by the bow modifications. It could therefore be hypothesized that there was a small but barely noticeable effect on all participants. This would mean that the confidence intervals for the joint kinematics in the present study are larger than those expected in normal conditions (i.e., this study is a worst-case scenario for kinematic variability). This effectively reduces the statistical power of the study, making it more conservative, which in turn should increase confidence in the significance of the results and the conclusions. On the other hand, a more appropriate design might have yielded more significant results that could have led to other conclusions.

Additionally, for the larger study, electromyography from indwelling EMG electrodes was acquired for three or four muscles (subject to the participant agreeing to this procedure). Even though no participants reported pain associated with these electrodes, about half reported feeling the electrodes throughout the data collection. These participants seemed more likely to rotate their shoulder between trials to relieve discomfort (not documented, simply informally discussed with the experimenters). The presence of the electrodes may have changed their kinematics pattern while playing. If so, however, it seems to have changed it consistently for each participant. The conclusions of the paper are therefore unlikely to have been affected by this.

Another limitation of the study was that only two bow strokes were tested, namely *legato* and *spiccato*. However, our own conclusions point to the need to include different bow strokes in a kinematics study on violinists. Other bow strokes in the violinist's toolbox include *ricochet**, *sautillé** or *tremolo**. These techniques may or may not affect joint kinematics. Our study did not allow us to conclude which bow strokes were (or were not) relevant. However, there are too many bow strokes to realistically expect any study to cover enough of them to be generalizable. One solution could be to choose a reference bow stroke and compare other bow strokes to it. An obvious choice is the *legato*, a stroke that uses most of the bow, does not involve any large accelerations, is one of the first bow strokes violinists learn, and seems to be used as a primary stroke[9,14].

Table 3: Recommendations when designing a bow-side joint kinematics study on violinists

Participants	Joint kinematics strategies are distinctive. Reporting the schools where participants studied is recommended to identify technique clusters.
Research Design	Due to the highly distinctive joint kinematics of the bowing arm, repeated measures experimental designs are recommended, with each participant serving as their own control.
Speed of play	Unless it affects bow stroking, playing speed does not seem to have much of an impact on joint kinematics (excluding joint velocity and acceleration studies). Therefore, a single velocity could be tested.
String played	The string played affects all the joints. Therefore, studies should test different strings, especially for arm elevation studies, where the effect is greatest.
Bow stroke	The bow stroke affects the whole upper limb, particularly the most lateral segments. Thus, it is essential to compare and contrast different bow strokes. Using a reference bow stroke such as the *legato* is recommended for ease of comparison between studies.
Analysis	Due to the closed kinematic chain inherent to violin playing, degrees of freedom are interdependent. This dependency should be appropriately addressed statistically.

5 Conclusion and recommendations

This study highlighted issues of variability in the analysis of joint kinematics of the bowing arm in violinists. The recommendations for standardizing methodology and data analyses generated from these findings could be integrated into future research to help reduce variability in results and increase the generalizability of conclusions.

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7 Declaration of interest statement

No potential conflict of interest was reported by the authors.

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Glossary

In order to help the readers without musical backgrounds, the following glossary of musical terminology used in this paper is provided:

Table 4: Glossary of musical terminology

Bar	Segment of time corresponding to a specific number of beats. The full collection of bars makes a score, i.e., a musical piece.
Bow stroke	A specific way to use the bow to produce a specific type of style of play (for instance *legato* or *spiccato*).
Bridge	A piece of wood that supports the strings on the violin.
Camber	The upward curvature of the bow along its long axis.
Down bow	A bow stroke which consists of moving the contact point of the bow with the violin from the frog towards the tip, effectively playing sound.
Fingering	The left-hand fingers sequence used to play a set of notes.
Frog	The end of a bow near the hand.
Legato	A long and continuous movement combined with a smooth transition that targets to remove all the silence between the current and the next note.
Nuance	The loudness of the play.
Piano	A soft nuance usually resulting in a calm sound.
Ricochet	An advance bow stroke that targets to bounces the bow rapidly and multiple times in a single down or up-bow*.
Sautillé	A bow stroke that targets to bounces the bow rapidly. It resembles the *spicatto*, but is usually faster.
Score	The written version of music.
Spiccato	A short movement with a lift of the bow between notes making a silence between the current and the next note.
Tempo	The speed of play. It is usually reported in beats-per-minute (noted bpm).
Tip	The end of the bow far from the hand.
Tremolo	A bow stoke consisting of very fast, small and repeated changes of direction. This is usually done piano* at the tip of the bow.
Up bow	A bow stroke which consists of moving the contact point of the bow with the violin from the tip towards the frog, effectively playing sound.

In order to help the readers without biomechanical backgrounds, the following glossary of biomechanics terminology used in this paper is provided:

Table 5: Glossary of biomechanical terminology

Acromioclavicular joint	The junction between the acromion of the scapula and the clavicle.
Closed-kinematic chain	Kinematic chain that loops, that is at least one of the nodes of the chain being a common parent.
Degrees of freedom (DoF)	Movement allowed between two segments of a kinematic chain. In three dimensions, there are at most three translations and three rotations.
Glenohumeral joint	The junction between the scapula and the humerus.
Kinematic chain	An assembly of rigid bodies connected by joints to provide constrained motion. The following body in the chain is call the child segment, while the previous segment is the parent segment.
Thoracohumeral joint	A pseudo-joint that represents a junction between the thorax and the humerus, effectively ignoring the clavicle and the scapula.