BIOMECHANICAL DIFFERENCES BETWEEN VIOLINISTS WITH AND WITHOUT NECK AND SHOULDER COMPLAINTS

MSc. Thesis

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ABSTRACT

Background:

Many professional violin players develop pain complaints in neck and shoulder regions as a result of prolonged practices containing highly repetitive motions and awkward postures. These complaints are often diagnosed as overuse syndrome, where physical changes are not apparent and of which the etiology is not yet understood. Mechanical overload might be part of the equation. Only limited research has been done to evaluate whether the biomechanics of violin playing differ between violinists with and without overuse syndrome. Muscle activity has been reported to differ between violinists with and without pain, but findings were often inconsistent. This study aims to evaluate the biomechanics of the musculoskeletal system in the neck and left shoulder region in violin players with and without pain complaints while playing different musical excerpts.

Method:

Twenty violinists, 10 with and 10 without pain complaints, were playing three musical pieces containing different wrist and bow motions. These were measured using motion capture and chin-violin force measurements. An upper body model was created by combining a neck model with a shoulder model in OpenSim, which was then used to calculate joint angles and moments of the neck and left shoulder. Differences in the kinematics and kinetics of violin playing were assessed by investigating mean values as well as the variability around these average values. The mean values of the joint angles and joint moments were compared over time during selections of bowing cycles and cycles of wrist movement. The kinematic variability was assessed with the standard deviations of the mean in each playing condition.

Findings:

Kinematic and kinetic differences were found between symptomatic and pain-free violinists during fast bowing motions. The axial rotation of the glenohumeral joint was significantly more external in violinists with overuse syndrome compared to controls. Additionally, joint moments in several degrees of freedom of the scapulothoracic and glenohumeral joints were larger in the symptomatic group compared to the asymptomatic group. Lastly, the kinematic variability of symptomatic violinists was lower than that of asymptomatic violinists.

Conclusion

These found kinematic and kinetic differences could mean that violinists with overuse syndrome play the violin with less optimal motor control, resulting in larger loads on the joints and surrounding tissues. The lower variability of kinematics in violinists with pain may indicate an increase in stiffness. Overall, these findings suggest that biomechanical differences exist between violinists with and without overuse syndrome.

INTRODUCTION

Many professional musicians develop playing-related musculoskeletal disorders, with prevalence ranging between 41—93% over a timespan of a year (Kok et al., 2016b). Complaints can be long-lasting and worsen when playing is continued, which is especially a problem for income-dependent professional musicians (Kok et al., 2016a). Problems arise especially often in string musicians, where 64.1-90 % suffer from musculoskeletal disorders and most commonly affect the neck, shoulders and upper extremities (Engquist et al., 2004; Kochem & Silva, 2018).

Most often, these musculoskeletal complaints are classified as overuse syndrome which is also known as repetitive strain disorder or cumulative trauma disorder (Bejjani et al., 1996; Lee et al., 2013). Patients suffer from complaints of pain, tenderness and loss of function but without pathology-related physical changes. The pain is often not localized and there is no objective diagnosis, but it is believed that overuse or misuse of body parts results in microtrauma in the tissues of muscles, tendons, nerves or bone (Bejjani et al., 1996; Buckle & Devereux, 2002; McInnis, 2020). The etiology however remains unknown and the onset of the disease is believed to be a result of a combination of influences (Armstrong et al., 1993; Buckle & Devereux, 2002; McInnis, 2020). Risk factors include highly repetitive motions, prolonged static loading, and extreme non-neutral postures, but influences from anxiety or ion concentrations may also play a role (Larsson et al., 2007; McInnis, 2020; Punnett & Wegman, 2004).

It is believed that professional string players such as violinists develop these complaints as a result of playing-related demands (Bejjani et al., 1996; Lee et al., 2013). In order to hold the violin in position, it needs to be clenched between the chin and left shoulder (Lee et al., 2013). The left hand needs to move freely over the violin neck to shift positions while fingers are pressing down the strings to play different notes and while the right arm is simultaneously stroking the bow over the strings.

It was found that violin playing kinematics and forces vary among individuals and may change with alterations in playing difficulty and with strings played (Kok et al., 2018; Kok et al., 2019; Obata & Kinoshita, 2012; Okner et al., 1997; Shan et al., 2003; Shan et al., 2007; Turner-Stokes & Reid, 1999; Wolf et al., 2019). Playing conditions of increasing difficulty even appear to significantly increase muscle activity and chin forces (Kok et al., 2018). After repeatedly practicing for many hours, many professional violinists develop musculoskeletal complaints, but not all (Kok et al., 2016b). In order to better understand the origination of these complaints, high string musicians with overuse syndrome have been compared to high string musicians without complaints. Activity of different neck and shoulder muscles was often reported to be increased in violinists with overuse syndrome (Kok et al., 2018; Möller et al., 2018; Park et al., 2012; Philipson et al., 1990; Steinmetz et al., 2016). Activity of the sternocleidomastoid muscle was repeatedly found to be higher in the complaint group, while findings regarding other muscles were not consistent among studies and deep muscles were not measured (Siemelink, 2020). Furthermore, research investigating kinematic and force differences between these groups is limited. Kok et al. (2018) examined and found no differences in the exerted force on the chin rest used to stabilize the violin between groups, while muscular activity in the neck was increased. Additionally, only one study compared kinematics between sitting violinists with and without neck complaints and found that neck rotation and lateral flexion angles were increased in the pain group as well as muscle activity (Park et al., 2012). In Park et al. (2012), ultrasonic motion analysis was used to assess cervical motion while violin players played a musical piece of medium difficulty. However, only one triple active marker was used, and no reference marker appears to have been used. It is therefore unclear if the measured angles represent neck motion or motion of the spine.

Comparisons between violinists with and without complaints have been made to discover whether the biomechanics of violin playing in symptomatic violinists are more harmful for tissues than in pain-free violinists. Since these studies were limited and findings were not always consistent, it is not yet clear whether these findings reflect functional differences between groups.

It may also still be possible that the reasons that some violinists develop complaints and others do not, have nothing to do with their violin playing techniques. The general violin playing technique contains risk factors for overuse syndrome such as asymmetric postures and static loading, but these risk factors are also present in pain-free violinists. Additionally, many influences appear to play a role in the complex origination of overuse syndrome. Daily posture during other activities or influences from stress or anxiety could for instance also explain why some violinists develop overuse syndrome and others do not.
In addition, the previously used biomechanical methods may not have been sensitive enough to discover differences, which may explain the inconsistent findings. For instance, surface electromyography (EMG) signals have often been used to measure muscle activity. This is however not the most precise measurement technique since signals easily get distorted and only superficial muscles are measured (Chowdhury, 2013; Konrad, 2006). More accurate methods are required and should also be used to study the kinematics of violin playing, since posture plays an important role in the onset of overuse syndrome but has barely been compared. A biomechanical simulation developed using software such as OpenSim (Delp et al., 2007; Seth et al., 2018) or AnyBody (Damsgaard et al., 2006), may be sensitive enough to discover kinematic and kinetic differences between groups when using accurate measurements as input. Discovering such differences may help identify the onset of the disease, explain previous findings and ultimately help to inform preventive measures and treatment of overuse syndrome. The aim of this study is therefore to determine whether biomechanical differences exist between violinists with and without neck and shoulder complaints.

Since non-neutral postures are considered to be risk factors for overuse syndrome and treatment is focused on posture improvement, it is reasoned that asymptomatic violinists are better at maintaining neutral posture while playing than symptomatic violinists. Neutral posture is considered as a resting position of the body where muscles and joints experience minimal tension and pressure (Andreoni et al., 2000; ErgoCenter at UConn Health Center, 2016; Tengwall et al., 1982). Mechanical loads on the neck may for example increase during neck flexion due to increased gravitational forces on the less well supported head (Neupane et al., 2017; Edmondston et al., 2011). Suboptimal postures may therefore increase muscle forces and joint moments, which could be injurious on surrounding tissues.

At the same time, it should be considered that movements are altered as a result of pain (Hodges et al., 2009). One theory argues that motor function is altered in order to protect injured tissues by limiting movement of the affected area's (Hodges et al., 2009; Hodges & Tucker, 2011). It is therefore also reasoned that the amount and size of movements will be lower in symptomatic violinists compared to asymptomatic violinists.

The following hypotheses will therefore be tested using a biomechanical model:

1. Neck and left shoulder positions from violinists with pain will be further from neutral position than in the posture of violinists without pain.

2. Neck and left shoulder joint moments from violinists with pain will be larger than joint moments of violinists without pain.

3. Kinematic variability in violinists with pain will be lower than in violinists without pain.

METHOD

Original experiment

Previously collected motion and force data of twenty subjects playing the violin were used (Kok et al., 2018, 2019). Motion capture, force and electromyography were measured while violinists were playing in different playing conditions and with different shoulder rest set-ups (Figure 1). The five playing conditions involved different musical pieces of varying difficulty. The twenty participants also filled in a questionnaire and were selected for the experimental group when reporting to experience complaints in neck and/or shoulder region at the time of measurement. The Neck Disability Index (NDI) and the Disabilities of the Arm, Shoulder and Hand (DASH) were also included in the questionnaire as an additional measure of pain. Forces applied by the head on the violin were measured with a 6-axis force and torque sensor incorporated into a chin rest (Kok et al., 2018). The inherently noisy x, y and z force components resulting from these measurements were corrected for offset and filtered with a second order Butterworth filter with a cutoff frequency of 3Hz.

Figure 1. Original measurement setup.

Skeletal model

An upper body skeletal model was created for kinematic and kinetic analyses using OpenSim 4.1 software (Figure 2). The model was constructed by combining a head and neck model (Mortensen et al., 2018) with a scapulothoracic model (Seth et al., 2016, 2019).

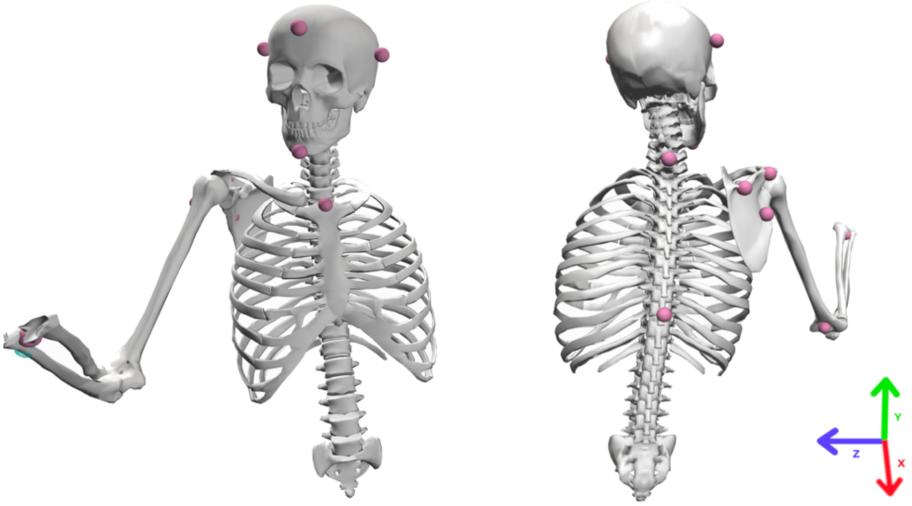

Figure 2. The upper body skeletal model in OpenSim. *The model is a reflection of the general violin playing posture, since the model only contains the right scapula while measurements were done with the left shoulder.*

The scapulothoracic model incorporates a right scapulothoracic joint which describes shoulder kinematics accurately enough to enable the differentiation between pain group and controls. The scapulothoracic joint includes the rotations and translations of the scapula with respect to the thoracic surface and has four degrees of freedom (Seth at al., 2016). Glenohumeral joint rotations were based on ISB-recommendations for joint coordinates systems, allowing three degrees of freedom (Seth at al., 2016; Wu et al., 2005). The model is a mirror image of the violin player, since only the right shoulder joint was included, while measurements were done with the opposite left shoulder. The existing head and neck model includes inertial properties and includes all cervical joints originating from two earlier cervical models, permitting more realistic dynamic analyses. Due to functional differences in the vertebrae of the cervical spine, movements of the superior vertebrae (Atlas and Axis) and the inferior vertebrae were separated. The motions of the cervical joints in each of these two groups were coupled which reduces the degrees of freedom of the neck to six (Mortensen et al., 2018).

The neck model was scaled to fit with the dimensions and mass of the scapulothoracic model. Afterwards, the scaled head, vertebral bodies and joints were added to the scapulothoracic model to make up the generic model with twenty-three degrees of freedom. The generic model includes bodies of the spine, thorax, cervical spine, head and the right scapula, clavicle and arm. Motion ranges of the joints were decreased to more realistic maximal values and joint constraints were adjusted to make relationships linear. Rotations of the cervical spine were coupled, constraining intersegmental rotations.

Data preparation

Motion capture and force data from the original measurements were applied to our model. Data was selected from three of the playing conditions when no shoulder rest was used. The playing conditions ‘first position’, ‘shifting’ and ‘virtuosic’ required different wrist and bowing techniques and are of increasing playing difficulty (Table 1).

Table 1. Playing conditions. *Three different musical pieces were played in the three playing conditions ‘first position’, ‘shifting’ and ‘virtuosic’. The table describes the motions of the three included playing conditions and whether or not a metronome was used in order to keep pace while playing.*

Playing condition	Motions	Metronome used?
First position	Left hand remains in first position while fingering (changing the placement of the fingers on the strings). The right arm is bowing in highly frequent motions with short strides.	Yes
Shifting	Right arm is bowing in low frequent motions with long strides. Motions also include shifting. During shifting, the left hand moves over the neck of the violin and shifts between positions.	Yes
Virtuosic	Motions include shifting of the left hand, low frequent bowing motions with long strides, as well as high-frequent short strides, fingering and vibrato. During vibrato, pitch oscillations are created by vibrating movements of arm, wrist or fingers. Violinists were instructed to play expressively.	No

The c3d files containing motion capture and force data were accessed using BodyMech 4.0 software and functions from the OpenSim API. Motion tracking markers on the left arm (lateral epicondyle, processus styloideus ulnae), left shoulder (acromion and two additional markers in cluster at fixed distance), spine (C7, Th10 and sternum jugular notch) and head (chin and three markers on a head band) were implemented (Figure 3). The motion capture data of these playing conditions also contains three markers placed on the violin. The marker data were rotated to transform the coordinates to the model coordinate system of OpenSim in MATLAB (MATLAB r2020b, The MathWorks, Inc., Natick, United States). The marker data were then reflected in the

y-axis, since the generic model contains a scapulothoracic joint of the right scapula while the movements of the static left shoulder had been tracked. This reflection relocates the markers of the left side of the body to the opposite right side of the body, allowing the use of the experimental markers of the left shoulder on the right scapulothoracic joint.
Additionally, the orientations over time of the scapula were calculated from the mirrored locations of the three scapula markers. The positions of two markers were used to define an axis in the plane of the scapula and two perpendicular axes were calculated using the third marker as well. These vectors were then converted to quaternions.

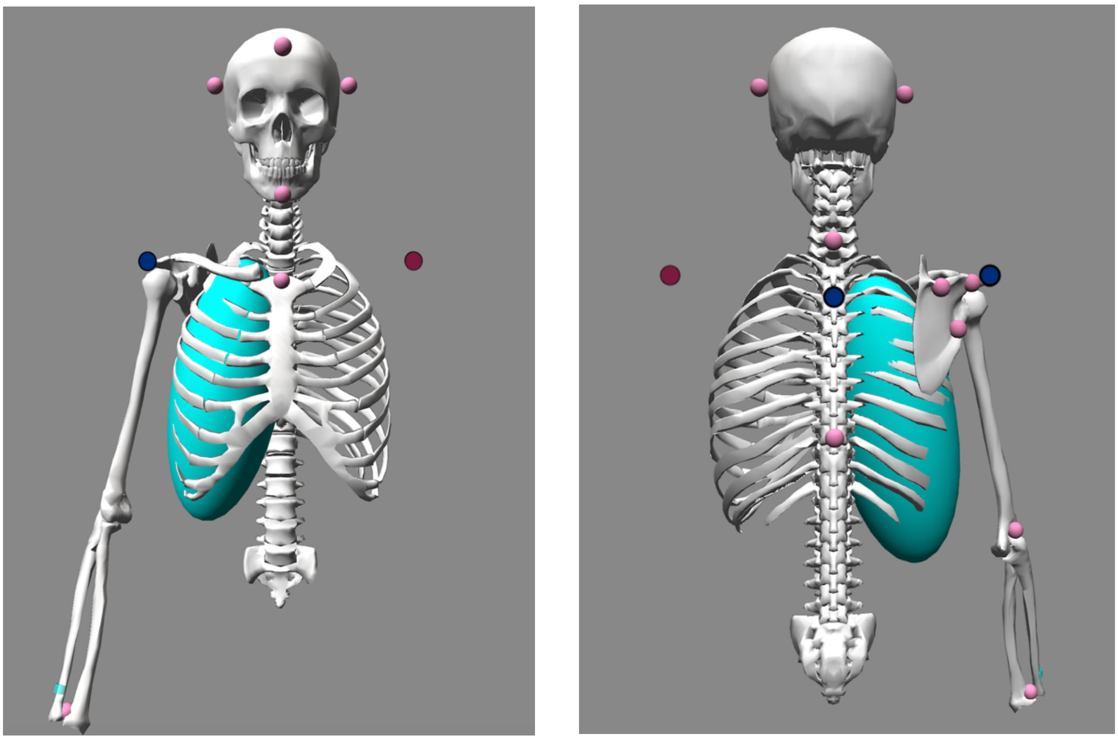

Figure 3. Experimental and virtual markers used for scaling. *The marker data and violin motions are mirrored and therefore the markers are shown on the opposite side of the torso. The experimental marker set (pink) includes two markers on the arm (lateral epicondyle and processus styloideus ulnae), three on the left shoulder (acromion and two additional markers in cluster at fixed distance), three on the spine (C7, Th10 and sternum jugular notch) and four on the head (chin and three markers on a head band). These pink experimental markers were used for the calculation of the inverse kinematics. Additionally, an experimental marker on the right shoulder (purple) was used for scaling as well as two virtual markers (blue).*

The filtered force data was rotated to adhere to OpenSim's coordinate system as well. The force data applied by the chin was used to represent the force applied by the violin on the shoulder. The opposite force directions were used to represent the reaction force of the violin on the chin. An additional c3d file was included containing motion tracking markers placed on the violin and on the chin rest. This file contains three markers placed on the violin on the same locations as in the experimental data and contains three additional markers surrounding the chin rest with the force sensor. The marker data were used to calculate the location of the force sensor on the model, after it was first also rotated to the coordinate system of the model in OpenSim and reflected in the y-axis. Then, the distance was calculated from the centre of the three violin markers to the centre of the three chin rest markers. Additionally, the three violin markers were used to calculate the orientation matrix which describes the orientation of the violin frame with respect to the global coordinate system. The inverse of this orientation matrix was used to calculate the distance between violin and force sensor in the global system. The three violin markers in all the experimental data files were then also used to calculate orientation matrices for all time samples. These time-varying orientation matrices were used to calculate the distance between the violin and force sensor in the local coordinate system of the violin in the experimental conditions (equation 1).

$$d_{experimental,t} = R_{experimental,t} \cdot inv(R_{calibration}) \cdot d_{calibration} \tag{1}$$

Where d is the distance between the violin and the force sensor, R are the rotation matrices from the experimental and calibration violins, and t are the time samples

This distance was added to the centre of the violin markers in the experimental files to find the location of the force sensor on the model (figure 4).

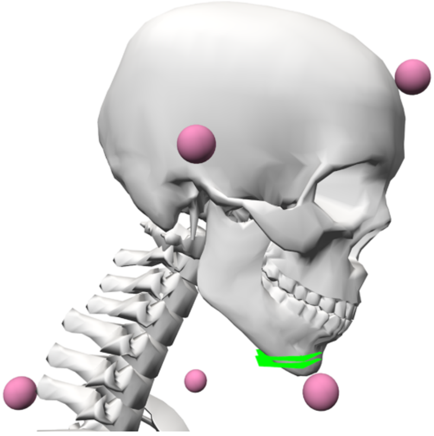

Figure 4. The upper part of the skeletal model with the location of the force sensor depicted in green.

Scaling

The generic model was scaled to the anthropometry and weight of the subjects by using the OpenSim ScaleTool. Distances between marker pairs on known anatomical landmarks were calculated and used to adjust the dimensions of the generic model to the individual. The x, y and z axes of the thorax, clavicle and scapula were scaled with separate scale factors which were calculated using experimental and virtual markers placed on the thorax (Figure 3). The scale factors applied to the remaining bodies were implemented the same on all three axes. Inertial properties of the scapulothoracic model had been based on the cadaver study by Klein Breteler et al. (1999), where the cadaver has a total mass of 67kg (Nikooyan et al., 2010). The proportion of the model's mass from the total mass of the cadaver was calculated in percentages. This mass percentage was multiplied with the subjects' total weight in order to find the mass of the scaled models.

Inverse Kinematics

The IMU Inverse Kinematics Tool (OpenSense) was used to calculate joint angles of the scapulothoracic joint from the orientation quaternions. These calculated angles were then implemented in the Inverse Kinematics (IK) Tool together with the optical motion capture marker locations to calculate the joint angles of the skeletal model. Only the locations of the experimental markers on the left arm, left shoulder, spine and head were used (Figure 3). The IK Tool calculates joint angles by solving for the weighted least squares problem in equation 2. The scapulothoracic joint angles calculated from the orientation quaternions were included here as experimental coordinate values. The minimal error is calculated for each time step. Both the summed difference between experimental markers and model markers as well as the summed difference between experimental coordinate values and IK-calculated coordinate values are taken into account. The orientation-based angles for the scapula were weighted equally as the motion capture locations. The remaining markers were all weighted equally as well, since the joints that are being studied did not contain markers on anatomical landmarks.

$$\underset{q}{min} \left| \sum_{i \in markers} w_i \left\| x_i^{exp} - x_i(q) \right\|^2 + \sum_{j \in unprescribed\ coords} \omega_j \left(q_j^{exp} - q_j \right)^2 \right| \tag{2}$$

Where q is de vector of generalized coordinates, w_i are the marker weights, x_i^{exp} are the experimental positions of markers i and $x_i(q)$ are the marker positions of the model. ω_j are the coordinate weights and q_j^{exp} are the orientation-derived angles.

Inverse kinematics results were evaluated in two ways. Firstly, the mean joint angles were compared to results from existing literature and had to remain within two standard deviations of previous reported values (Hicks et al., 2015). Secondly, marker errors calculated in the least squares equation were assessed. These differences between experimental and model markers were evaluated to have RMS values smaller than 2 centimeters and maximal errors smaller than 2-4 centimeters (*Getting Started with Inverse Kinematics*, n.d.).

Inverse Dynamics

The Inverse Dynamics (ID) Tool was used to calculate joint moments of the created biomechanical model. The ID tool calculates net joint moments by solving the equations of motion in equation 3. The generalized positions, velocities and accelerations were determined from the previously calculated joint angles. These joint angles were first filtered with a second order low pass Butterworth filter with a cutoff frequency at 2Hz. Reaction forces from the violin on the chin were applied as external forces on the jaw. An equal and opposing force was applied on the scapula to represent the force exerted by the violin on the shoulder.

$$T = M(q)\ddot{q} - G(q) - C(q,\dot{q}) - A(q,\dot{q},t,x) \tag{3}$$

Where position, velocity and acceleration vectors $q, \dot{q}$ *and* $\ddot{q}$ *are determined from the kinematic input. T are the generalized forces which are calculated, M is the Mass matrix, C the Coriolis and Centrifugal forces, G the system gravity and A are the applied loads.*

It is recommended to evaluate ID results by comparing the calculated joint moments to results from existing literature (Hicks et al., 2015). An additional recommended assessment of the dynamic consistency could not be applied to our model since ground reaction forces were not included and our model is not connected to ground.

Post-processing

Joint angles and moments of the scapulothoracic, glenohumeral and the cervical joints were used in our analyses (Table 2).

Table 2. Included joint angles of the scapulothoracic, glenohumeral and cervical joints.

Scapulothoracic	Genohumeral	Cervical
Abduction	Plane elevation	Flexion
Elevation	Elevation	Lateral flexion
Upwards rotation	Axial rotation	Rotation
“Winging” / Internal rotation		

The cervical spine in the model contains seven cervical vertebrae and their joint angles and moments were summed together for each degree of freedom to represent the angles of the entire cervical spine. Then, the joint angles and moments of the twenty subjects were aligned over time using a Dynamic Time Warping (DTW) algorithm (MATLAB and Signal Processing Toolbox r2020b, The MathWorks, Inc., Natick, United States). This algorithm aligns the time duration of the samples from the different subjects. There were large differences in time duration in the virtuosic condition, but differences were also present in other conditions where a metronome was used. Two samples are optimally matched by finding the indices that minimize the Euclidean distance d in Equation 4. The distances of forward bow marker motions from the samples of all subjects were compared and optimally matched with the sample of the subject with the longest time duration in each condition (Appendix: Figures A1-A4). The data from the motion tracking markers on the bow were used because these contained the clearest patterns over time. The indices calculated for these matches were then also used to match the joint angles and moments for that same condition.

$$d = \sum_{\substack{m \in ix \\ n \in iy}} \sqrt{\sum_{k=1}^{K} (x_{k,m} - y_{k,n}) \cdot (x_{k,m} - y_{k,n})} \tag{4}$$

where d is the Euclidean distance, x are the samples of the subjects, y is the sample of the subject with the longest time duration in that condition, ix and iy are the indices and m and n the time samples.

The neck angle directions of the model depict the coordinates of neck extension and right lateral flexion as positive numbers. The signs of these coordinates were therefore changed to more typical conventions where positive angles represent neck flexion, left lateral flexion and left rotation.

Selection ‘submotions’

Since many simultaneous movements are involved in violin playing, different aspects of playing movements or ‘submotions’ needed to be separated. This was also necessary because different musical pieces, varying in tempo and technical difficulty, appeared to affect playing biomechanics (Berque & Gray, 2002; Kok et al., 2018; Obata & Kinoshita, 2012; Okner et al., 1997).
In the three included playing conditions violinists were playing three different musical fragments which contained different motions and techniques of the bow and wrist (Table 1). Movement patterns were most clearly visible in the motion tracking markers of the bow and arm (Appendix: Figures A1-A4). Therefore, after dynamic time warping, these were used to select different submotions from the playing conditions after which were used for further analysis (Table 3).

Table 3. Selected submotions from the different playing conditions. *In the three playing conditions three different musical pieces were played (Table 1). These musical pieces required different techniques of fingering, bowing, shifting and vibrato. This table shows the different submotions that were selected from the three playing conditions and included bowing and shifting cycles. During shifting, the wrist moves over the neck of the violin and shifts between positions. The mean joint angles and moments during these submotions were compared between symptomatic and asymptomatic violinists.*

Playing condition	**Submotions**
First position	Fast and short bowing cycle
Shifting	Slow and long bowing cycle
	Shifting cycle
Virtuosic	Variable bowing cycle

In each condition a bowing “cycle” was selected, where the bow first moves downwards and then back upwards (Figure 5). Additionally, a wrist shifting “cycle” was selected in the playing condition ‘shifting’, where the wrist first moves to the left of the violin neck and then back to the right (Figure 6). The bowing and wrist motions in the ‘virtuosic’ condition were however not repetitive, but a sub selection of the bowing motion was also included. Since this playing condition was technically demanding, studying the kinematics and kinetics during such a sub selection may still be of value.

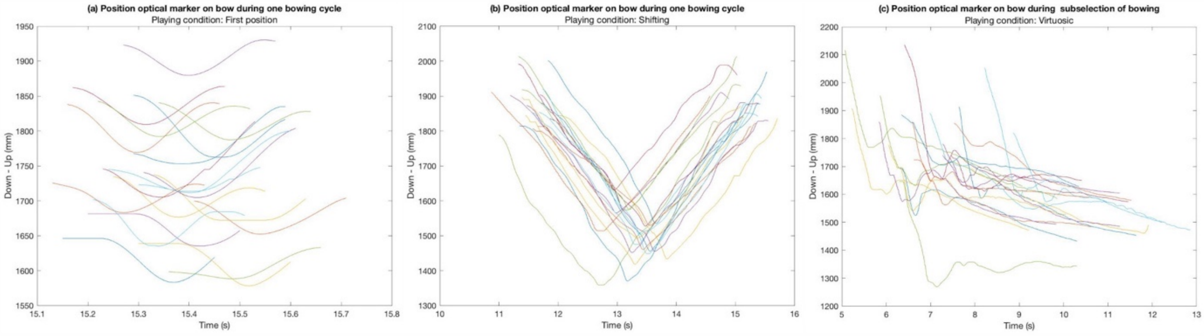

Figure 5. Selected bowing submotions from different playing conditions. *A selection of a bowing cycle in the playing conditions ‘First position’ (a) and ‘Shifting’ (b) are shown. In the ‘Virtuosic’ playing condition, no repetitive motions were present, but a bowing sub selection was used (c).*

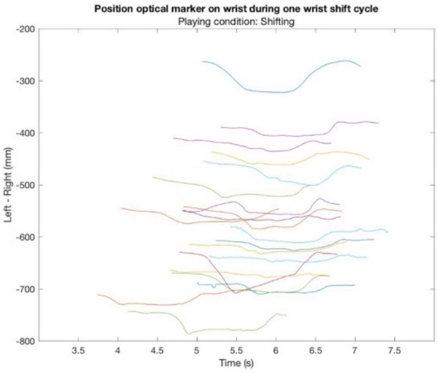

Figure 6. Selected wrist submotion from playing condition 'Shifting'.

The cycles were selected by finding peak values in the dynamically time-warped bow and wrist marker data (Appendix: Figures A1-A4). The starting point of a "cycle" is selected by finding the maximum in a short time period of the data. The same number of time samples are included in a "cycle" for all subjects starting from the slightly different starting points. Multiple cycles, selected from different time periods, were compared for each submotion.

Data analysis

The three hypotheses were compared in different ways using different parameters:

1. The average joint angles of the neck and left shoulder were compared between the symptomatic group and the control group. Mean values were compared over time during all selected submotions. Since mean angles could be more positive or more negative, a two-tailed test was used.

2. Similar as with joint angles, the group means of neck and shoulder joint moments were compared between symptomatic and asymptomatic violinists. Comparisons were made over time during the selected submotions and since joint moments can differ in both directions, a two-tailed test was required.

3. The kinematic variability of all the joints in the model were compared between groups for each excerpt. For each subject the standard deviations of the joint angles were calculated as a measure of variability. The kinematic variability of all the model's degrees of freedom were considered. In addition to the previously mentioned neck and shoulder rotations, the model includes rotations of the elbow, clavicle and rotations and translations of the thorax with respect to the ground. Forearm pronation was however not be considered since only one wrist marker was applied during measurements and this degree of freedom could therefore not be measured. The magnitude of the translation vector was used to describe the translations of the thorax with respect to ground. Standard deviations were calculated from the time-varying joint angles of the entire musical fragment. The standard deviations of symptomatic subjects were compared to the standard deviations of control subjects in a one-tailed test.

The Statistical Parametric Mapping software SPM1D 0.4 was used in MATLAB for statistical analysis. SPM1D can be used for hypothesis testing of one-dimensional measurements and is suitable for making statistical inferences of time-varying measurements (Pataky, 2010). One-dimensional tests were applied on the hypotheses of the time-varying mean joint angles and moments, while zero-dimensional tests were used for the standard deviation values. The two populations were compared using parametric two sample t-tests. If, however the assumptions of this parametric test were not met, median values were compared using the nonparametric Mann-Whitney U test instead. The significance level was set at $\alpha<0.05$.

RESULTS

Validation Inverse Kinematics
The calculated joint angles were compared to previous literature in order to validate them. Figure 7 depicts the joint angles of one subject in the playing condition ‘First position’.

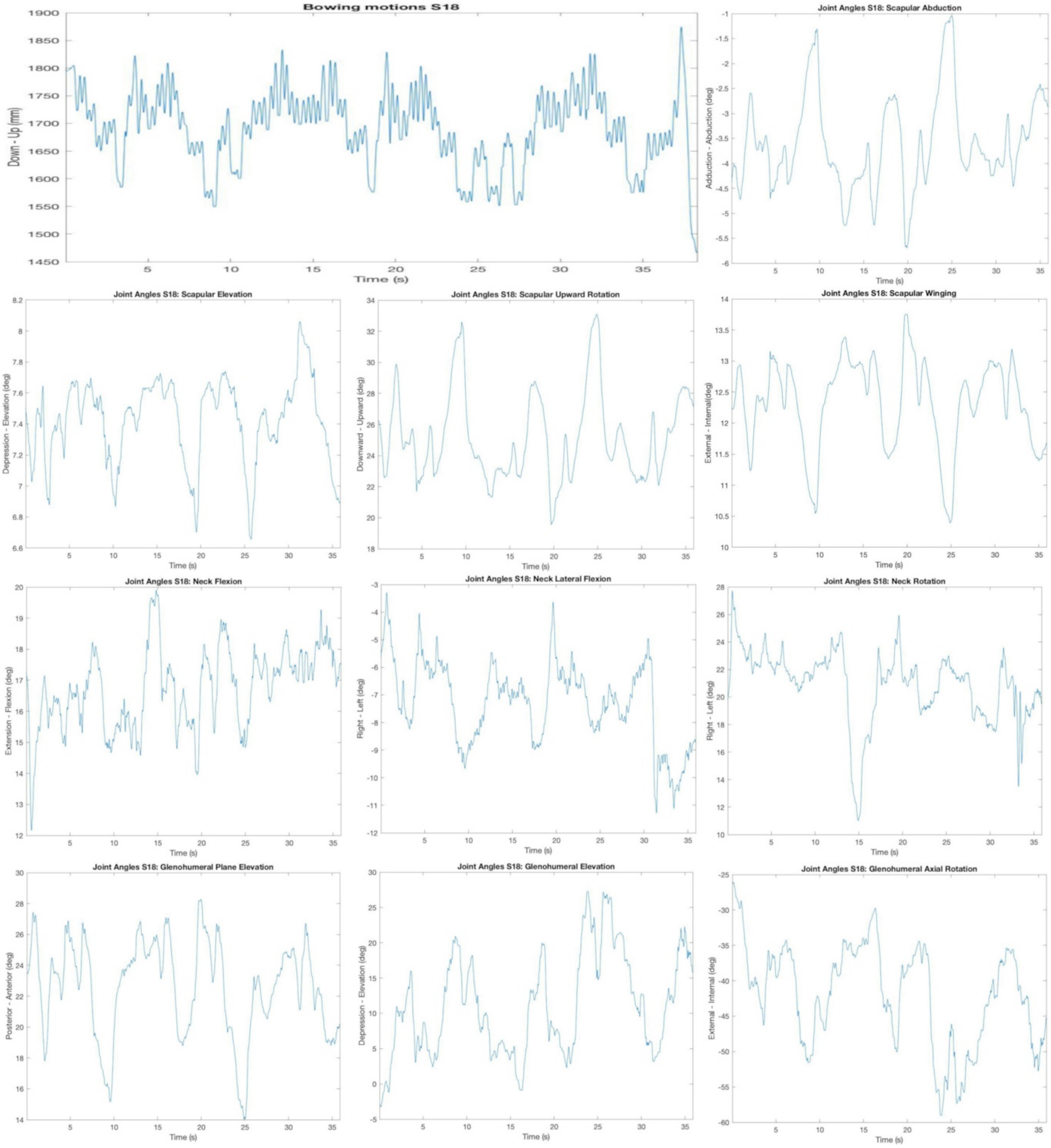

Figure 7. The bow motion and joint angles of one subject during the playing condition ‘First position’. *The figure shows the upwards and downwards motions of the optical marker placed on the bow. In addition, the joint angles over time of the cervical, scapulothoracic and glenohumeral joints are depicted.*

The mean joint angles of the neck were compared to previously reported values in the literature measured during violin playing motions (Table 4a-b). The mean cervical joint angles of all three conditions were within two standard deviations of the reported values from Park et al. (2012).

Table 4a. Mean cervical joint angles and standard deviations (in degrees) of control and pain group during different playing conditions. *The table shows the found results of the group averages (μ) and standard deviations (σ) from the flexion, lateral flexion and rotation angles in the playing conditions 'first position', 'shifting' and 'virtuosic'. The average and standard deviation values in the 'virtuosic' condition are calculated from the time samples between 3 and 16 seconds which were included in the data analysis.*

	Controls						Symptomatic					
	Flexion		Lateral flexion		Rotation		Flexion		Lateral flexion		Rotation	
CONDITION	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
First position	13.2	4.8	-4.9	7.2	12.9	12	12.5	7.5	-3.9	7.1	14.9	12.8
Shifting	17.6	6	-0.4	7.4	5.1	14.8	15.2	9.4	-3.1	7.3	12	14.8
Virtuosic	15.8	8.1	-2.8	8.5	11.4	17.6	13.7	9.8	-2.8	9.8	14.2	15.4

Table 4b. Previously reported mean cervical joint angles (in degrees) of control and pain group. *The table shows flexion, lateral flexion and rotation angle ranges reported by other articles. New findings should fall within joint angle ranges of two standard deviations (σ) from the mean value (μ) of previous findings.*

	Controls						Symptomatic					
	Flexion		Lateral flexion		Rotation		Flexion		Lateral flexion		Rotation	
CONDITION	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Park et al. (2012)	14.62	5.39	1.37	5.46	4.87	4.49	9.35	5.46	5.84	2.41	10.47	5.07

No values had been reported for scapulothoracic joint angles of the left shoulder. Shan & Visentin (2003) did report glenohumeral joint angles of the left shoulder, but these were not comparable since different definitions for the joint coordinate system were used. Bowing kinematics of the right shoulder were described more often in literature but were not comparable due to the different involved kinematics (Ancillao et al., 2017, Duprey et al., 2021, Shan et al., 2007; Turner-Stokes & Reid, 1999).

Additionally, differences between model and experimental markers during kinematics were verified to remain low. The maximal errors were lower than 4 centimeters and RMS values were lower than 2 centimeters for all subjects in the playing conditions 'first position' and 'shifting' as recommended (Table 5). In the virtuosic condition these thresholds were exceeded for some subjects at certain moments in time. At these times, markers were misplaced, or measurement data was missing. It was assumed by me that these reported marker values were not correctly being measured by the system, as a result of occlusion of the markers and tracking problems. These data samples of the virtuosic condition were excluded from the time samples used in data analysis and the remaining marker errors were mostly below thresholds. The data samples between 3 and 16 seconds remained and were used for further analysis (Appendix: Figure A4).

Table 5. RMS and maximal marker errors during scaling and inverse kinematics. *The table shows the RMS and maximal values of differences between the model markers and experimental markers of all 20 subjects. Marker error values of scaling as well as inverse kinematics of the playing conditions 'first position', 'shifting' and 'virtuosic' are shown. Scaling and inverse kinematics estimates were validated by examining if marker errors are low enough. RMS values should be lower than 0.02m and maximal values should be lower than 0.04m. The orange-colored values exceeded these thresholds.*

Condition	Scaling		**First Position** Inverse Kinematics		**Shifting** Inverse Kinematics		**Virtuosic** Inverse Kinematics	
	RMS (m)	Max (m)	RMS (m)	Max (m)	RMS (m)	Max (m)	RMS (m)	Max (m)
Subject 1	0.008	0.012	0.013	0.029	0.014	0.032	0.014	0.029
Subject 2	0.01	0.016	0.013	0.033	0.013	0.03	0.012	0.027
Subject 3	0.008	0.014	0.013	0.028	0.014	0.028	0.014	0.025
Subject 4	0.01	0.018	0.01	0.025	0.01	0.022	0.009	0.021
Subject 5	0.009	0.015	0.01	0.021	0.009	0.019	0.016	0.043
Subject 6	0.009	0.017	0.01	0.021	0.012	0.025	0.010	0.022
Subject 7	0.009	0.018	0.01	0.018	0.011	0.019	0.010	0.020
Subject 8	0.008	0.014	0.009	0.021	0.01	0.021	0.011	0.024
Subject 9	0.01	0.019	0.015	0.038	0.011	0.022	0.013	0.032
Subject 10	0.01	0.018	0.01	0.02	0.01	0.019	0.010	0.021
Subject 11	0.007	0.013	0.011	0.024	0.009	0.016	0.010	0.018
Subject 12	0.008	0.013	0.012	0.028	0.013	0.028	0.011	0.025
Subject 13	0.008	0.018	0.012	0.026	0.009	0.017	0.010	0.018
Subject 14	0.009	0.015	0.012	0.028	0.012	0.03	0.011	0.020
Subject 15	0.009	0.013	0.011	0.024	0.01	0.021	0.010	0.019
Subject 16	0.009	0.018	0.011	0.022	0.012	0.024	0.012	0.022
Subject 17	0.008	0.014	0.015	0.031	0.015	0.032	0.014	0.030
Subject 18	0.01	0.02	0.006	0.014	0.007	0.017	0.006	0.015
Subject 19	0.009	0.016	0.009	0.019	0.009	0.018	0.009	0.016
Subject 20	0.008	0.013	0.011	0.02	0.011	0.022	0.014	0.027

Validation Inverse Dynamics

The joint moments of one subject in the playing condition ‘First position’ are shown in figure 8.

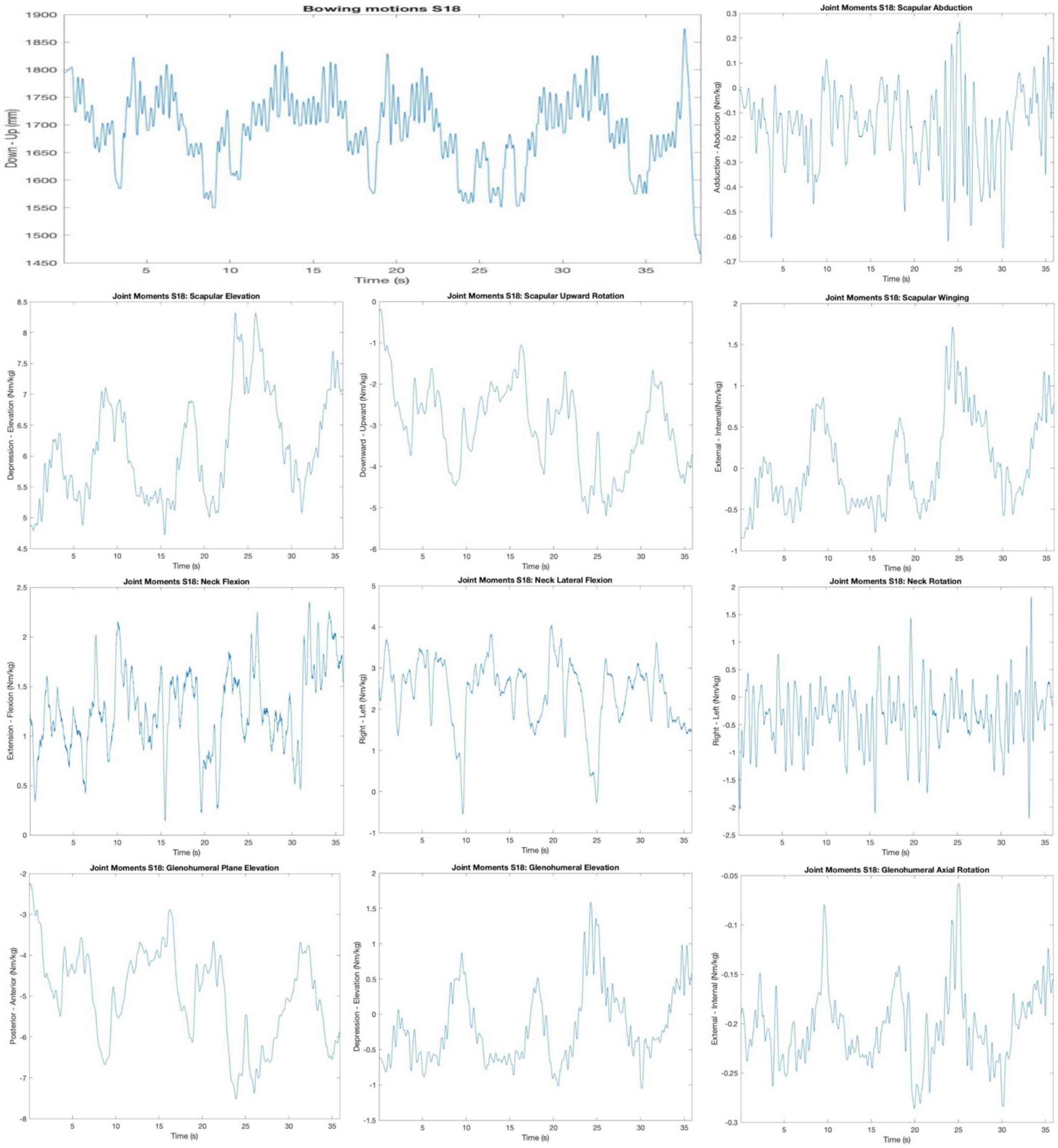

Figure 8. The bow motion and joint moments of one subject during the playing condition ‘First position’. *The figure shows the upwards and downwards motions of the optical marker placed on the bow. In addition, the joint moments over time of the cervical, scapulothoracic and glenohumeral joints are depicted.*

It was recommended to assess the validity of the joint moments by comparing our results to previously reported findings. Not many previous studies have however examined the kinetics of violin playing. Only one research group has measured joint moments of the shoulders in violin playing (Shan et al. 2004; Shan et al., 2007; Visentin & Shan, 2003). However, since the shoulder was regarded as a single joint with one degree of freedom and often only included the right shoulder in their studies, these values could not properly be compared to our findings. There was therefore no applicable way to validate our ID results.

Joint angles

The mean joint angles of glenohumeral external rotation differed significantly between symptomatic and asymptomatic violinists during bowing cycles of the playing condition ‘First Position’ (Table 6). There were no other no significant differences in the mean joint angles of violinists with and without complaints in the scapulothoracic, glenohumeral and cervical joints during any of the other selected submotions.

Table 6. Significant differences in mean joint angles (in degrees) during the selected motion cycles at 15.1-15.8s of condition ‘first position’. *The table shows the averaged joint angles over a bowing cycle of the symptomatic (sympt.) and control (contr.) groups (while statistical testing was done across the time-interval). In addition, the effect size is expressed as the difference between group means and and the p-values at a significance level of <0.05 are shown. Only the mean joint angles of glenohumeral axial rotations differed significantly between groups during small bowing cycles of the playing condition ‘first position’.*

	Motion	P - value	Mean Contr. (deg)	Mean Sympt. (deg)	Effect size (Contr. - Sympt.)
First position: Bowing cycle	Glenohumeral axial rot.	0.029	-34.28	-45.77	11.48 deg

Glenohumeral external rotation angles were significantly more external in symptomatic violinists over the whole bowing cycle, compared to controls (Figures 9 & 10).

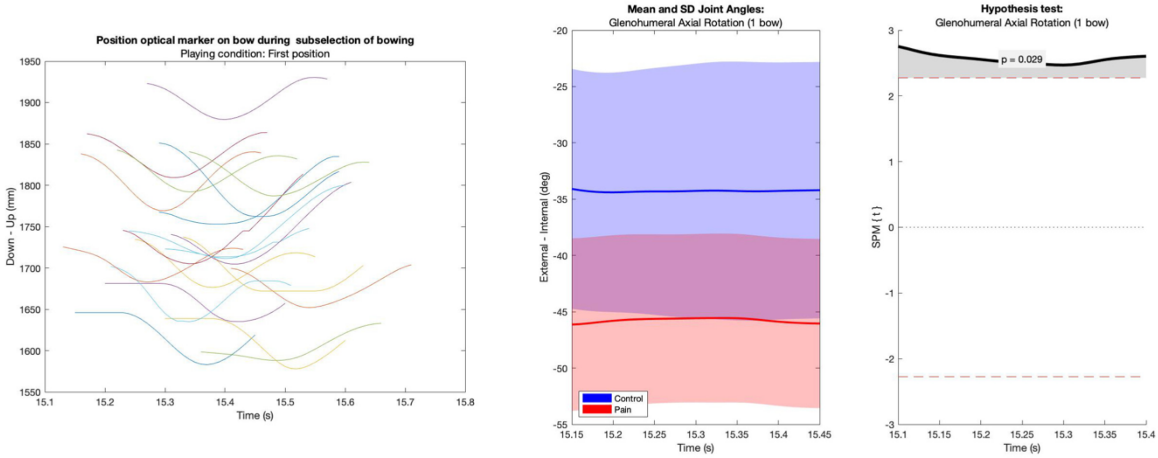

Figure 9. Mean glenohumeral axial rotation joint angles during one bowing cycle at 15.1-15.8s of playing condition ‘First position’. *The selected bowing cycles of all 20 subjects are shown on the left. The mean joint angles of symptomatic violinists (red) and asymptomatic violinists (blue) during this bowing cycle are shown in the middle figure. The standard deviation (SD) is represented with the shaded area. The statistical test in spm1d (right) shows that the glenohumeral axial rotation angles differ significantly between groups during this subselection.*

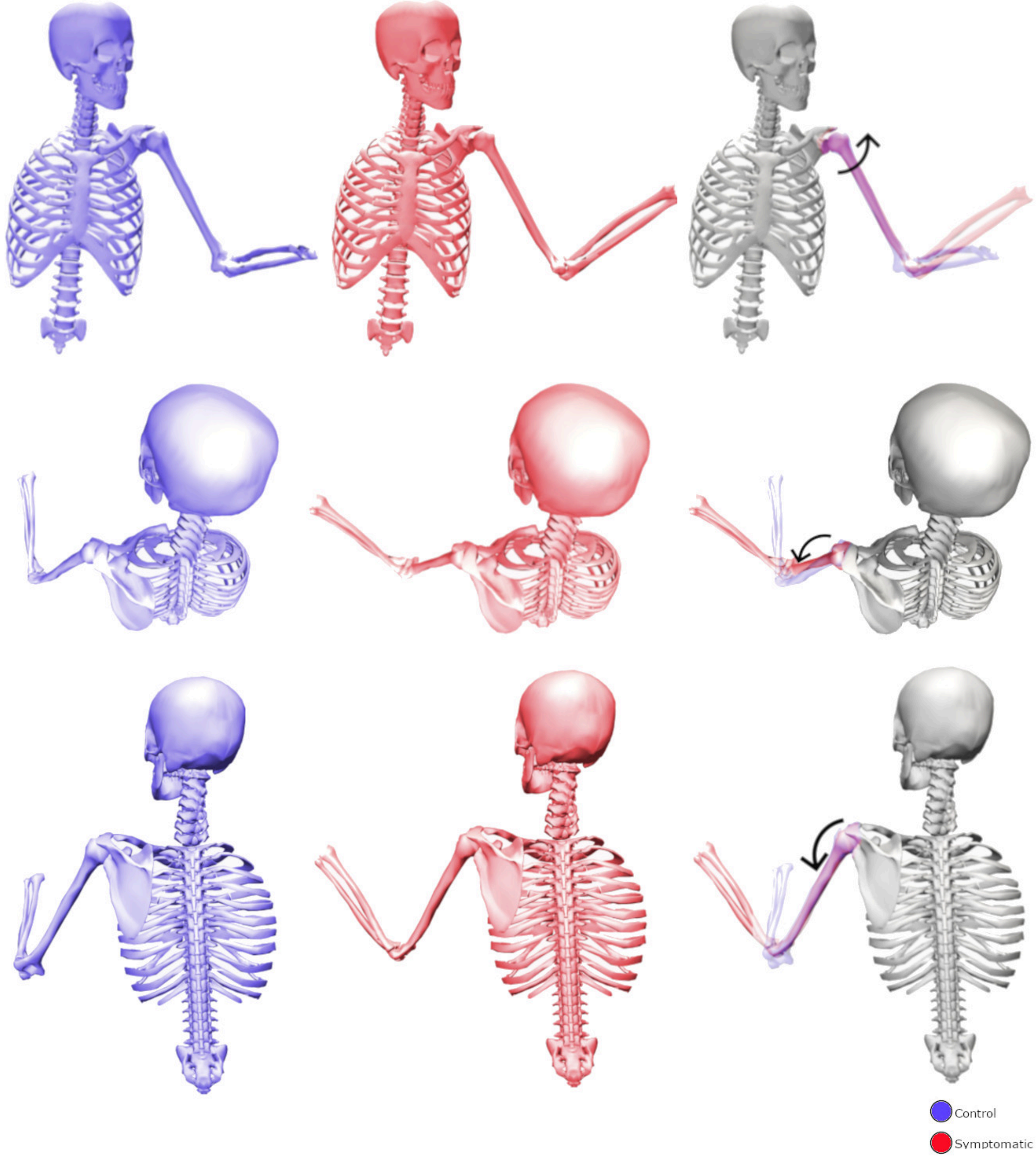

Figure 10. Differences in the glenohumeral axial rotation joint angles between symptomatic and asymptomatic violinists. *The figure shows exaggerations of the found differences of glenohumeral axial rotation joint angles during small bowing cycles of playing condition 'First position'. The symptomatic posture is depicted in red, and the asymptomatic posture is depicted in blue. The figure on the right shows the overlap between symptomatic and asymptomatic postures. The arrows depict the rotational change of the symptomatic posture with respect to the asymptomatic posture.*

This difference in glenohumeral axial rotation joint angles between symptomatic and asymptomatic violinists is unrelated to the selected time sample. Ten bowing cycles were selected at different points in time and the same effect was found every time. The joint angles of glenohumeral external rotations were significantly larger in symptomatic violinists in all ten cycles.

Also in the other conditions, multiple cycles were selected for analysis. In the condition 'shifting', three bowing and shifting cycles were compared but no differences in joint angles between groups were found in any of these cycles. It was however not possible to compare more than one sub selection in the condition 'virtuosic', due to the limited number of remaining data samples.

In addition, it should be noted that similar differences in the glenohumeral axial rotation joint angles are present between symptomatic and asymptomatic groups during the entire playing condition as during the selected bowing cycle, though these are not significantly different (Figure 11).

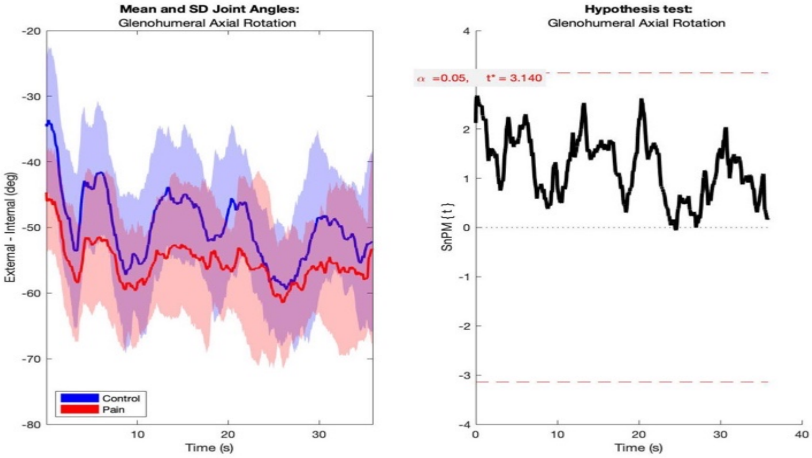

Figure 11. Mean glenohumeral axial rotation joint angles during the entire duration of playing condition ‘First position’. *The mean joint angles of symptomatic violinists (red) and asymptomatic violinists (blue) are shown in the left figure. The standard deviation (SD) is represented with the shaded area. The statistical test in spm1d (right) shows that the glenohumeral axial rotation angles are not significantly different. This was similar to other degrees of freedom in this playing condition.*

Lastly, it can be observed that inter-subject variation of joint angles within each group is large, as can be seen in figure 12. The inter-subject variation of joint angles is large in all joints in all playing conditions.

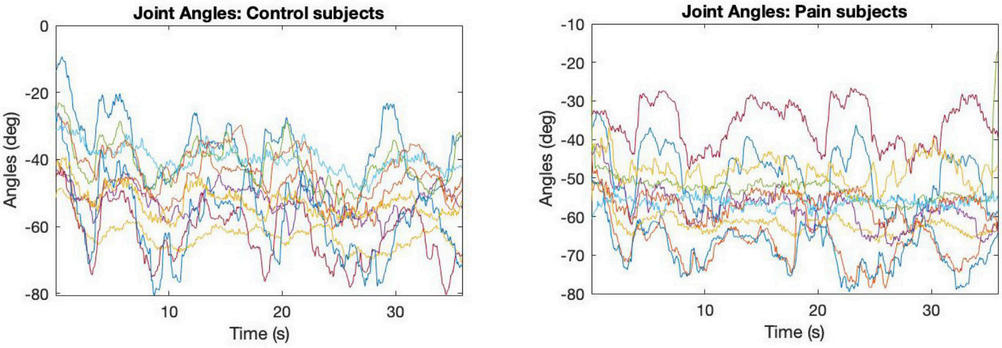

Figure 12. Glenohumeral axial rotation joint angles of all 20 subjects during the entire duration of playing condition ‘First position’. *The joint angles of the ten asymptomatic violinists are shown in the left figure and the joint angles of the ten symptomatic violinists are shown in the right figure. This was similar to other degrees of freedom.*

Joint moments

Significant differences in mean joint moments were found between symptomatic and asymptomatic violinists during bowing cycles of the playing condition ‘First Position’ (Table 7). The mean joint moments of scapular upward rotation, scapular elevation, scapular winging and glenohumeral plane elevation differed significantly between groups. No differences were found in the other playing conditions.

Table 7. Significant differences in mean joint moments (in Nm/kg) during the selected motion cycles at 15.1-15.8s of condition ‘first position’. *The table shows the averaged joint moments over a bowing cycle of the symptomatic (sympt.) and control (contr.) groups (while statistical testing was done across the time-interval). In addition, the effect size is expressed as the difference between group means and and the p-values at a significance level of <0.05 are shown. The mean joint moments of scapular elevation, scapular upwards rotation, scapular winging and glenohumeral plane elevation differed significantly between groups.*

	Motion	P - value	Mean Contr. (Nm/kg)	Mean Sympt. (Nm/kg)	Effect size (Contr. - Sympt.)
First position: Bowing cycle	Scapular elevation	0.001	5.11	6.66	-1.55 Nm/kg
	Scapular upw. rotation	0.007	-0.69	-4.19	3.50 Nm/kg
	Scapular winging	0.042	-1.07	-0.13	- 0.94 Nm/kg
	Glenohum. plane elev.	0.013	-3.45	-6.40	2.95 Nm/kg

Joint moments of scapular upward rotations were more downwards, while scapular elevation was more elevated in symptomatic violinists compared to controls (Figure 13). In addition, scapular winging joint moments were less external (relatively more internal) and glenohumeral plane elevation was more posterior. These differences in joint moments would push the joints towards different postures as is visualized in figures 14 and 15. NOTE that these two figures only visualize in which degrees of freedom differences in joint moments were found and do NOT represent actual kinematic differences.

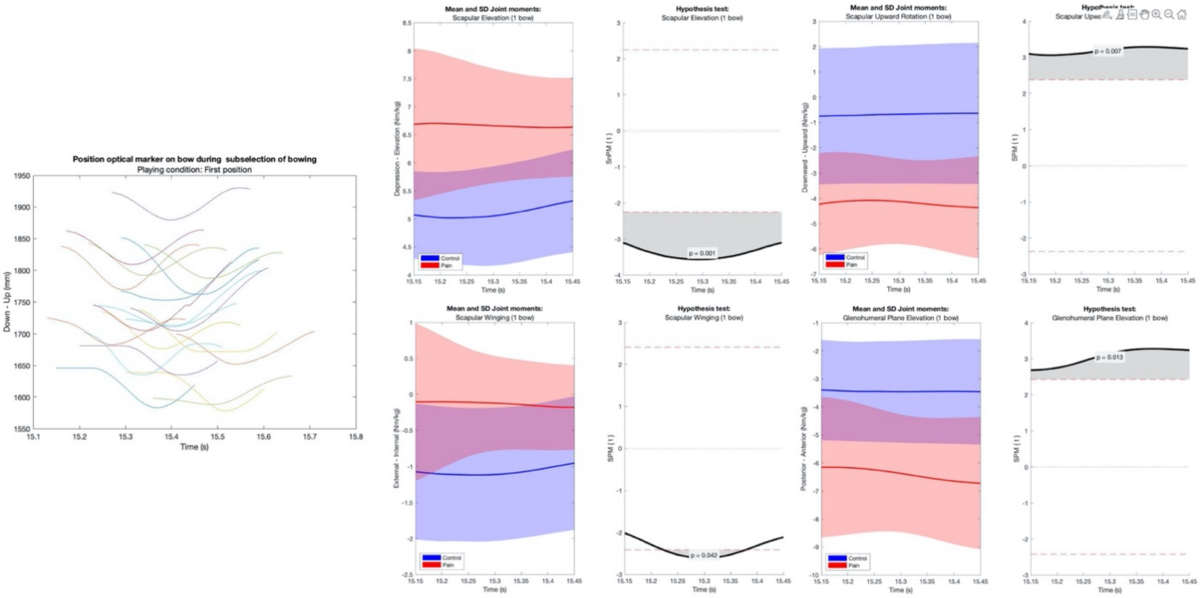

Figure 13. Mean joint moments of scapular elevation, scapular upwards rotation, scapular “winging” or internal rotation and glenohumeral plane elevation during one bowing cycle at 15.1-15.8s of playing condition ‘First position’. *The selected bowing cycles of all 20 subjects are shown on the left. The figure shows the mean joint moment values of symptomatic violinists (red) and asymptomatic violinists (blue) during this bowing cycle in the figures on the right together with the statistical tests. The standard deviation (SD) is represented with the shaded area. The statistical tests in spm1d show that scapular elevation, scapular upward rotation, scapular winging and glenohumeral plane elevation moments differ significantly between groups during this subselection.*

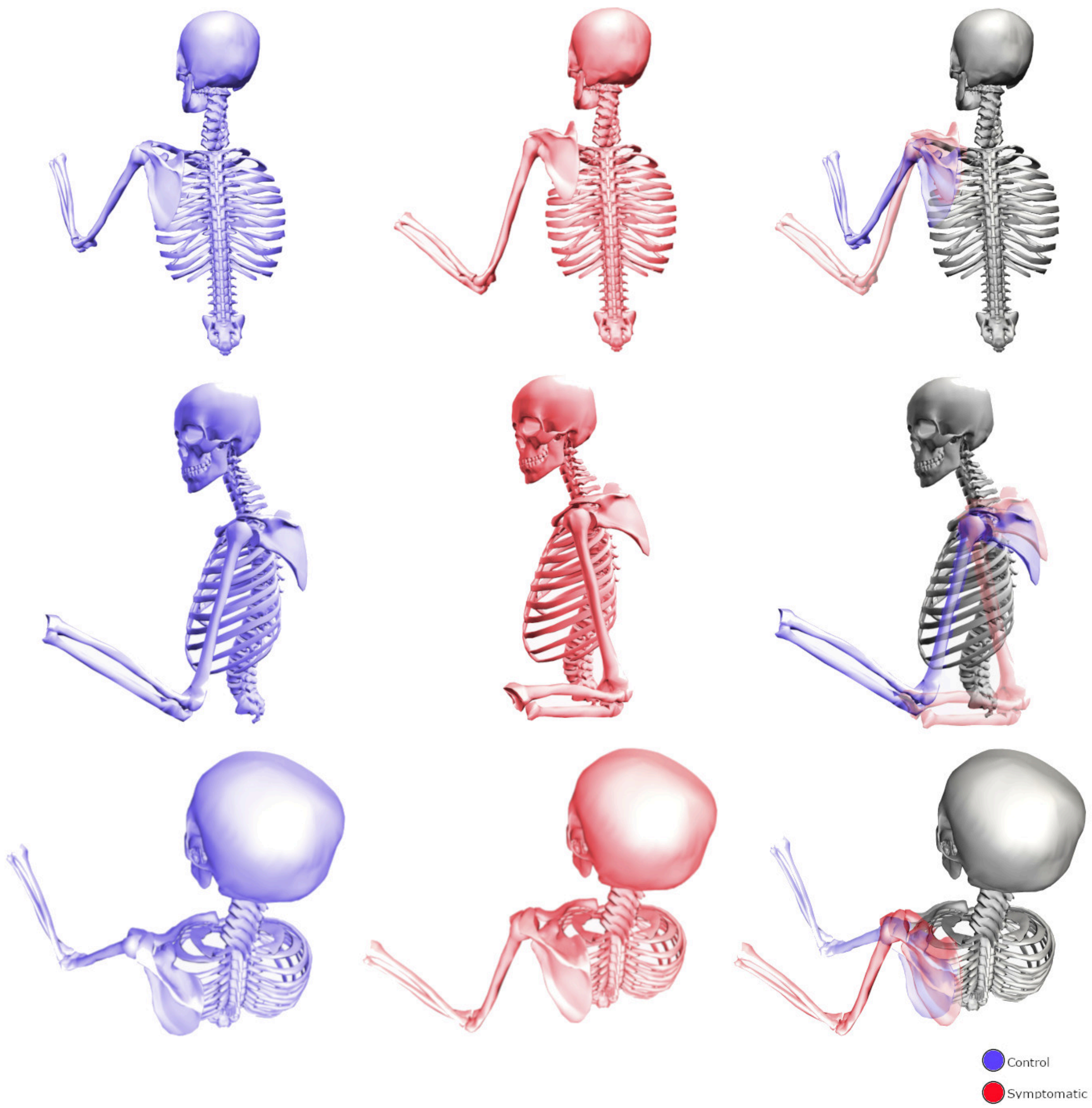

Figure 14. Differences in the joint moments between symptomatic and asymptomatic violinists – visualized as differences in posture. *Scapular elevation, scapular upwards rotation, scapular "winging" or internal rotation and glenohumeral plane elevation joint moments differed between groups during small bowing cycles of the playing condition 'First position'. The differences in mean joint moments that were found WOULD direct the joints towards the different postures that are depicted. The figure shows exaggerations of these consequential differences in postures between symptomatic and asymptomatic violinists in order to visualize the directions of the joint moments. The symptomatic posture is depicted in red, and the asymptomatic posture is depicted in blue. The figure on the right shows the overlap of symptomatic and asymptomatic postures. In the figure on the right the joints are colored in purple when structures of the symptomatic and asymptomatic groups overlap.*

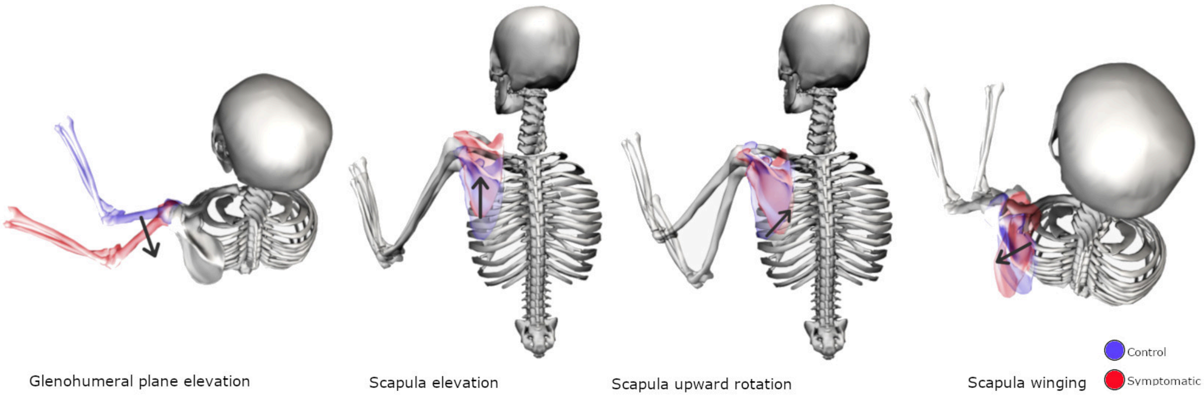

Figure 15. Differences in the separate joint moments between symptomatic and asymptomatic violinists – visualized as differences in posture. *Glenohumeral plane elevation, scapular elevation, scapular upwards rotation and scapular "winging" or internal rotation joint moments differed between groups during small bowing cycles of the playing condition 'First position'. The differences in mean joint moments that were found WOULD direct the joints towards the different postures that are depicted. The figure shows exaggerations of these consequential differences in postures between symptomatic and asymptomatic violinists in order to visualize the directions of the joint moments. In order to clarify the directions of the four joint moments, the four degrees of freedom are depicted separately. The arrows illustrate the direction of movement from the asymptomatic posture towards the symptomatic posture. In each figure, the posture of the symptomatic group (red) is shown together with the posture of the asymptomatic group (blue).*

To ensure that these effects were related to the selected bowing motions, ten separate bowing cycles were studied. Significant group differences in scapular elevation, scapular upwards rotation and glenohumeral plane elevation joint moments were found in all ten cases. Group differences in scapular winging joint moments were significant in seven cycles. Three separate bowing cycles were studied in the playing condition 'shifting' and only one cycle in the condition 'virtuosic', but findings were not significant in any of these cases.

Similar to the differences in joint angles, the differences in the joint moments during the entire playing condition are comparable to those of the selected bowing cycles but are not significantly different (Figure 16).

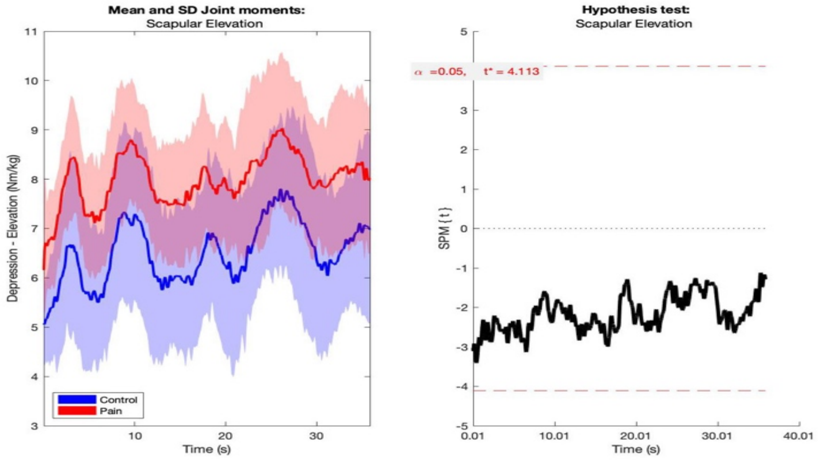

Figure 16. Mean scapular elevation joint moments during the entire duration of playing condition 'First position'. *The mean joint moments of symptomatic violinists (red) and asymptomatic violinists (blue) are shown in the left figure. The standard deviation (SD) is represented with the shaded area. The statistical test in spm1d (right) shows that scapular elevation joint moments are not significantly different. This was similar to other degrees of freedom in this playing condition.*

Much inter-subject variation is also present in the joint moments of the symptomatic and asymptomatic groups. Figure 17 shows this inter-subject variation for scapular elevation joint moments.

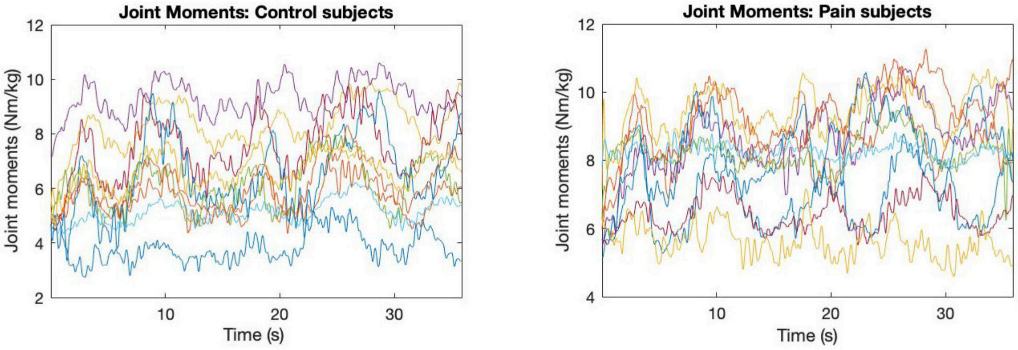

Figure 17. Scapular elevation joint moments of all 20 subjects during the entire duration of the playing condition 'First position'. *The joint moments over time of the ten asymptomatic violinists are shown in the left figure and the joint moments over time of the ten symptomatic violinists are shown in the right figure. This was similar to other degrees of freedom.*

Kinematic variability

Standard deviations of ground-thorax, glenohumeral and cervical joint angles were significantly lower in the symptomatic group compared to the controls in the playing conditions 'first position' and 'shifting'. Such a difference in standard deviations of the group averages can be observed in figure 18, where the group averages of ground-thorax translations are displayed during 'shifting'.

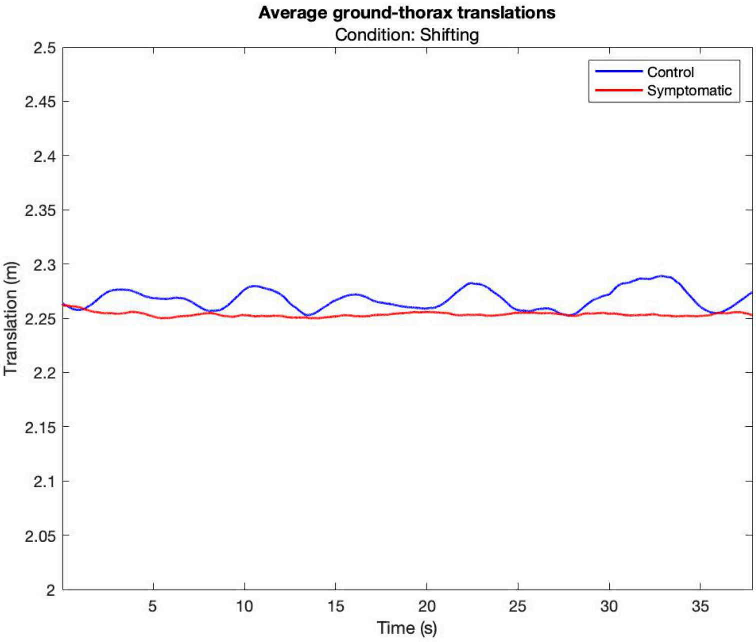

Figure 18. Average ground-thorax translations of symptomatic and asymptomatic violinists in the playing condition 'shifting'. *The figure depicts the magnitude of the x-, y-, and z-translations of the thorax with respect to ground. It can be seen that the deviations from the mean are larger in the control group (blue) compared to the symptomatic group (red).*

The standard deviation values, statistical findings and effect sizes of the joint angles in all three playing conditions are shown in table 8. Values are depicted in green when standard deviation values of symptomatic violinists are significantly lower than those of asymptomatic violinists.

Table 8. Standard deviations of the joint angles in the three playing conditions. *The table shows the group means of the standard deviations (STD) from the symptomatic (sympt.) and control (contr.) groups in degrees (deg) or meters (m). In addition, the effect size is expressed as the difference between group means and the p-values at a significance level of <0.05 are shown. Significant differences (**) between symptomatic and controls are depicted in green. Findings were significant when the standard deviations of the joint angles from symptomatic violinists were significantly lower than those from asymptomatic violinists. No significant differences were found in the 'virtuosic' condition*

Playing condition	Motion	P- value	STD Contr. (deg)	STD Sympt. (deg)	Effect size (Contr. - Sympt.)
First position	Scapular Abduction	0.385	0.92	0.86	0.06 deg
	Scapular Elevation	0.473	0.31	0.30	0.01 deg
	Scapular Upward Rotation	0.535	1.68	1.71	-0.03 deg
	Scapular Winging	0.610	0.40	0.43	-0.03 deg
	Neck Flexion	0.113	1.79	1.38	0.40 deg
	Neck lateral flexion **	0.019	1.95	1.22	0.73 deg
	Neck Rotation	0.227	2.10	1.82	0.28 deg
	Glenohumeral Plane El.	0.763	1.61	1.86	-0.25 deg
	Glenohumeral elevation **	0.027	6.82	4.90	1.92 deg
	Glenohumeral axial rot. **	0.034	6.58	4.55	2.03 deg
	Ground-thorax rot. x-ax **	0.020	2.25	0.95	1.31 deg
	Ground-thorax rot. y-ax **	0.008	2.92	1.55	1.37 deg
	Ground-thorax rot. z-ax **	0.026	3.20	1.83	1.37 deg
	Ground-thorax transl. **	0.006	0.025 m	0.009 m	0.016 m
	Clavicle protraction	0.404	0.77	0.74	0.03 deg
	Clavicle elevation	0.554	0.53	0.55	-0.02 deg
	Elbow flexion	0.941	1.12	1.39	-0.3 deg
Shifting	Scapular Abduction	0.482	0.75	0.74	0.01 deg
	Scapular Elevation	0.198	0.26	0.21	0.05 deg
	Scapular Upward Rotation	0.322	1.23	1.08	0.14 deg
	Scapular Winging	0.388	0.31	0.28	0.03 deg
	Neck Flexion	0.073	2.46	1.70	0.77 deg
	Neck lateral flexion **	0.002	2.34	1.20	1.14 deg
	Neck Rotation	0.161	2.97	2.30	0.68 deg
	Glenohumeral Plane El.	0.228	2.63	2.38	0.25 deg
	Glenohumeral elevation **	0.015	12.79	8.99	3.80 deg
	Glenohumeral axial rot. **	0.010	11.79	7.79	4.00 deg
	Ground-thorax rot. x-ax	0.055	1.67	0.98	0.69 deg
	Ground-thorax rot. y-ax **	0.017	2.75	1.44	1.31 deg
	Ground-thorax rot. z-ax	0.120	2.00	1.29	0.71 deg
	Ground-thorax transl. **	0.001	0.018 m	0.005 m	0.014 m
	Clavicle protraction	0.156	0.65	0.54	0.11 deg
	Clavicle elevation	0.608	0.34	0.37	-0.03 deg
	Elbow flexion	0.966	4.68	5.51	-0.83 deg
Virtuosic	Scapular Abduction	0.482	0.87	0.85	0.023 deg
	Scapular Elevation	0.923	0.27	0.41	-0.14 deg
	Scapular Upward Rotation	0.686	1.90	2.13	-0.24 deg
	Scapular Winging	0.568	0.48	0.50	-0.02 deg
	Neck Flexion	0.25	2.86	2.34	0.52 deg
	Neck lateral flexion	0.623	2.47	2.76	-0.29 deg
	Neck Rotation	0.636	3.37	3.91	-0.55 deg
	Glenohumeral Plane El.	0.820	3.01	3.74	-0.73 deg
	Glenohumeral elevation	0.115	4.30	3.45	0.85 deg
	Glenohumeral axial rot.	0.144	5.28	4.36	0.92 deg
	Ground-thorax rot. x-ax	0.094	2.25	1.59	0.66 deg
	Ground-thorax rot. y-ax	0.397	4.14	3.86	0.28 deg
	Ground-thorax rot. z-ax	0.220	3.39	2.69	0.70 deg
	Ground-thorax transl.	0.440	0.021 m	0.020 m	0.001 m
	Clavicle protraction	0.743	0.69	0.89	-0.20 deg
	Clavicle elevation	0.775	0.66	0.83	-0.17 deg
	Elbow flexion	0.391	7.30	7.15	0.16 deg

DISCUSSION

The aim of this study was to elucidate biomechanical differences between violinists with and without neck and shoulder complaints. This was done by comparing joint angles, joint moments and kinematic variability of the neck and left shoulder between violinists with and without neck and shoulder complaints during different violin playing motions.

Interpretation of the findings: Average joint angles and moments
Significant differences were found in the average joint angles and joint moments between groups during one short bowing motion in the playing condition 'first position'. The joint angles of glenohumeral axial rotations were significantly larger and more externally rotated in symptomatic violinists compared to asymptomatic violinists. Joint moments of scapular upward rotation, scapular elevation, scapular winging and glenohumeral plane elevation were significantly larger in symptomatic violinists compared to controls. These same group differences were repeatedly found in ten different selections of short bowing cycles and were therefore not dependent on one specific small bowing cycle. The consistency of these findings reinforces the notion that this effect is present in the population.

The average joint angles and joint moments from the entire duration of the playing condition differed in a similar way between groups but were not significantly different due to large variability. This may be related to differences in the compared movements of the subjects. The bowing motions from the different subjects were not well-aligned and were not the same. Due to these discrepancies and misalignments, the data could not reliably be compared over the entire time frame, since the compared time samples could involve different motions. However, when ten different selections of short bowing cycles of this playing condition were compared, group averages differed significantly during all selected bowing cycles. These ten bowing cycles were selected at different points in time and did not include the exact same time samples for each subject. The bowing motions included in these selections were better aligned and more comparable between subjects. Joint angles and joint moments during these sub selections of bowing motions may therefore have been more meaningful to compare than during the entire playing condition. This could explain why group differences were much clearer and were significant during the selected bowing cycles and not during the entire playing condition.

Furthermore, no differences were found in the mean joint angles and moments between groups in the other two playing conditions, which mainly involved slow and large motions of the bow. Differences in joint angles and moments between the symptomatic group and the controls were only found during short and fast bowing motion cycles. Even though the position of the bow on the violin differed in these selected bowing cycles, findings were similar and significant. The found effects are therefore probably not dependent on the position of the right bowing arm but likely are dependent on the short and fast motions of the bow.

These results therefore indicate that differences exist in the posture and mechanical loading of the left shoulder between symptomatic and asymptomatic violinists during fast bowing motions. This could mean that some violinists develop neck and shoulder complaints because they play the violin with a less neutral posture and endure more mechanical load on their shoulder joints than violinists without such complaints.

Interpretation of the findings: Joint angle variability
Kinematic variability was significantly lower in symptomatic violinists compared to asymptomatic violinists. Lower variability of lateral neck flexions, glenohumeral elevations, glenohumeral axial rotations, ground-thorax rotations and ground-thorax translations were found in the playing conditions 'first position' and 'shifting'. In the virtuosic condition, no differences in kinematic variability between groups were found. This may be related to the instructions that violinists received in the virtuosic condition. Violinists were instructed to play expressively, which may have resulted in larger and more joint motions in all violinists.

These findings indicate that violinists with complaints are moving their neck and left shoulder joints as well as their thorax less than violinists without complaints. Our model does not include any lower body joints or thoracic, lumbar, and sacral joints. The found differences in the motions of the thorax with respect to ground may therefore also include motions of the spine, hips, and legs. Since differences in rotation of the thorax were also found, it is not unlikely that motions of the lower spine are involved.

A possible explanation for this decrease in moveability is an increased stiffness of joints in the left shoulder and spine in violinists experiencing pain in order to protect painful regions. According to the pain adaptation model, activity of agonistic and antagonistic muscles is altered to reduce pain and protect injured structures (Hodges & Tucker, 2011; Lund et al*.,* 1991). At the same time, it is believed that co-contraction of antagonistic muscles increases muscular and joint stiffness (Hodges et al., 2009; Thelen et al., 1995; Stokes et al., 2006). This may in turn improve stability and resistance against perturbations or compensate for dysfunctional muscular control.
It is however also possible that symptomatic violinists develop complaints as a result of decreased joint movement. This may for instance indicate that symptomatic violinists have more tension in the spine and shoulders to begin with.

Comparison to earlier findings

In contrast to the findings from Park et al. (2012), the average joint angles of the cervical joints did not differ significantly between violinists with and without neck and shoulder complaints. These differences in findings may be a result of differences in data analysis. Park et al. (2012) used time-averaged joint angles which included different violin playing motions in their study. In this study, different playing aspects were separated and examined over time. Additionally, Park et al. (2012) appear to have included the rotation angles of the entire spine instead of only of the cervical spine. This could also mean that rotational differences exist between groups in other sections of the spine. Since our model however did not contain thoracic, lumbar, or sacral joints and motions of the spine had not been measured, no conclusions can be drawn on kinematic differences of other parts of the spine.

In previous studies, the muscular activity of the neck and shoulders was compared and was often reported to be increased in violinists with neck and shoulder complaints compared to asymptomatic violinists (Kok et al., 2018; Möller et al., 2018; Park et al., 2012; Philipson et al., 1990; Steinmetz et al., 2016).
Such increases in neck and shoulder muscle activity may represent increases in muscle force. Since kinematic and kinetic differences were found between groups in this study, it is possible that this increased muscle activity in symptomatic violinists signifies increases in rotational movements. On the other hand, our findings also suggest that differences exist in the amount of kinematic variability of symptomatic violinists compared to asymptomatic violinists. Violinists that are enduring pain exhibit increased stiffness. In this case, higher muscular activity may signify increased co-contraction of antagonistic muscles, which opposes agonistic muscle function and is believed to increase muscular and joint stiffness (Hodges et al., 2009; Thelen et al., 1995; Stokes et al., 2006). This agrees with earlier findings that showed a consistent increase of the activity in both sternocleidomastoid muscles and high correlations between the activity of both sternocleidomastoid muscles (Kok et al., 2018; Park et al., 2012; Steinmetz et al., 2016). However, it should also be kept in mind that increased muscle activity does not necessarily imply an increase in muscle contractions. The measured myographic signals represent electric potentials of motor units, but the resulting applied forces also depend on several properties of the motor units (Enoka & Duchateau, 2015). It is for instance also possible that the same electrical stimulation elicits a less effective contractile response in the muscles of symptomatic violinists and that muscle activity needs to increase to obtain the same contraction force.

Lastly, the variation of joint angles and moments between subjects was high for all joints in this study. In earlier studies, large inter-subject differences were also discovered in motions of the bowing arm (Yagisan et al., 2009; Michaud et al., 2021). This would indicate that different violin playing strategies exist and also that they are not solely related to pain complaints since these interindividual differences existed in both groups.

Limitations

It needs to be considered that the data samples in the selected submotions that were compared may not coincide completely between individuals. The start of the bowing cycle was not the exact same datapoint in time for each subject since the starting point was selected as the maximum value in a short time period of the data. While this tactic makes the compared cycles more comparable, it is not certain that the selected submotions of all ten subjects were the exact same part of the song. However, since the small bowing cycles were selected within a time frame of 0.6s and one cycle has a duration of 0.3s, such discrepancies remain limited.

Additionally, the compared submotions were selected from playing conditions involving other simultaneous motions. During the condition “shifting” violinists were making large but slow bowing motions but were simultaneously shifting their wrist back and forth over the violin neck. It was not possible to separate these simultaneous movements completely and these may therefore have been confounding.

An additional limitation of this study is that the experimental group included violinists with both neck and/or (bi)lateral shoulder complaints of varying severity. No distinctions were made between the location and the severity of the complaints within the experimental group. However, it is possible that the etiology of neck complaints differs from the etiology of shoulder complaints. The regression analysis of Kok et al. (2018) showed a significant positive correlation between the chin force and the severity of shoulder complaints, while correlations between the chin force and pain complaints were not significant. This could indicate that differences in complaint types may give different results.

Furthermore, it should be kept in mind that even though the differences between experimental and model markers were below recommended values, RMS errors were still quite large. This introduces uncertainty in our findings. The number of possible solutions to the least squares equations decrease as RMS errors decrease. As a result, the chance of finding the most accurate solution increases as well as the likelihood that our simulations represent the true situation.

Lastly, the interactions between pain and movements need to be considered. While pain is a symptom of overuse syndrome, pain is also believed to alter movements. A person experiencing pain may adapt or avoid movements in a variety of ways and it is therefore unclear if differences in movement are part of the cause or the effect of pain (Hodges & Smeets, 2015). In this study, the kinematics of violinists were investigated, who were already experiencing pain at the time of measurement. It is not known whether the measured kinematics are the same kinematics that initiated pain complaints. The found kinematic and kinetic differences between groups may therefore signify causes of overuse syndrome as well as adaptations to pain.

Conclusion:

This was the first study comparing the kinematics and kinetics of violin playing between violinists with and without overuse syndrome using a biomechanical model. The kinematics and kinetics of the left shoulder from symptomatic violinists differed from pain-free violinists during fast bowing motions. This could indicate that symptomatic violinists play the violin with a less neutral posture and with larger joint loads on the left shoulder than asymptomatic violinists. However, since our findings include uncertainties, the possibility that these findings may reflect errors in measurements should also be considered. In addition, the kinematic variability of symptomatic violinists was lower than in pain-free violinists, which may indicate an increase in stiffness around the joints. Overall, our findings suggest that biomechanical differences exist between violinists with and without neck and shoulder complaints, but more research is needed to be able to verify and fully understand their meaning.

Future studies:

Future studies should aim to localize the origin and involved structures of the complaints, to separate causes of pain from its' effects, and to eliminate confounders as much as possible. While our findings suggest that the playing kinematics and kinetics of violinists with overuse syndrome are different from those of pain-free violinists, uncertainties in these findings remain. Confirming these findings in future studies would be useful and should involve more targeted research.

Such studies should involve more comparable motions. Only one specific motion should be measured at a time, which should be repeated multiple times for each subject. Considering only one motion will eliminate influences from confounding motions and increase the likelihood that signals from different subjects coincide and align. Repeating these measurements will decrease the intrasubject variability and improve signal to noise ratio. Furthermore, it should be investigated if the large inter-subject variability can be explained and if it can be decreased by making subjects within a group more comparable. The sizing of subjects should be considered, since differences in length, neck length and shoulder width are likely to have an influence on playing kinematics. Additionally, subjects that are experiencing pain in the left shoulder, right shoulder and neck should be investigated separately since different tissues may be involved. Lastly, it would also be interesting to investigate and compare the kinematics and kinetics of joints in the spine, the bowing shoulder, and upper extremities since these are also often affected in overuse syndrome.

Alternatively, prospective studies can be used to investigate how complaints develop. This way, causes can be separated from its' effects, although such studies may not be practical to implement. Finally, studies at a cellular level will improve our biological understanding of overuse syndrome. These can be used to test theories regarding adaptations in the sensory nervous system and the motor system, such as adaptations in nociception or in motor unit characteristics.

Altogether, these studies could help us to discover if and how the biomechanics of violin playing can be improved. This may improve our understanding of overuse syndrome and may help to prevent it.

APPENDIX

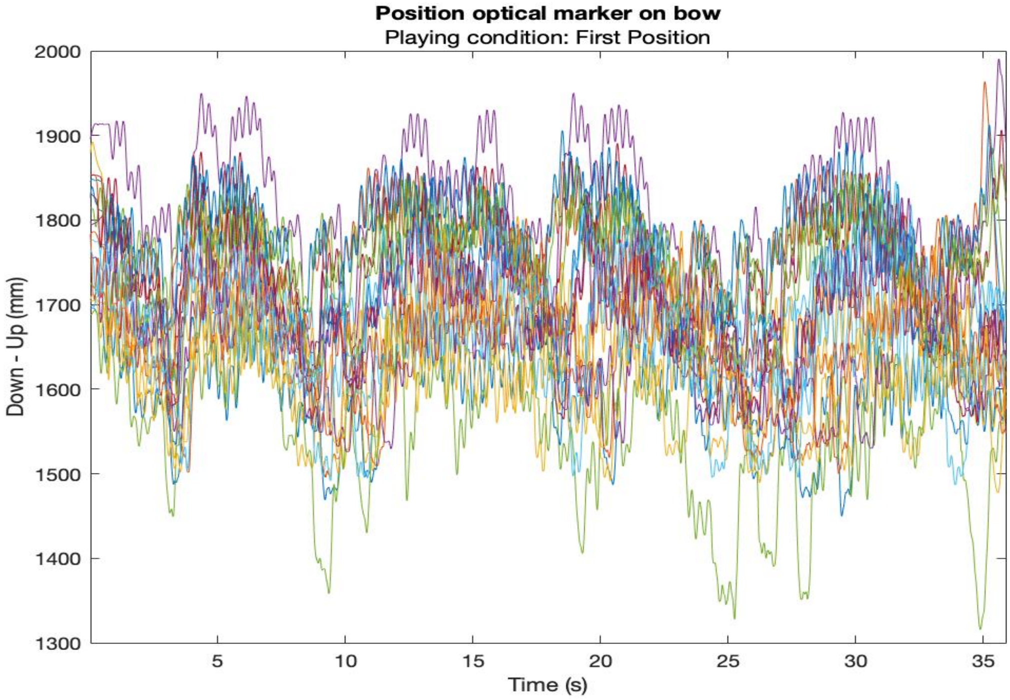

Figure A1. Bowing motion during condition ‘first position’. *Figure shows the upwards motions of the bow during fast and short bowing from the twenty subjects after dynamic time warping was performed.*

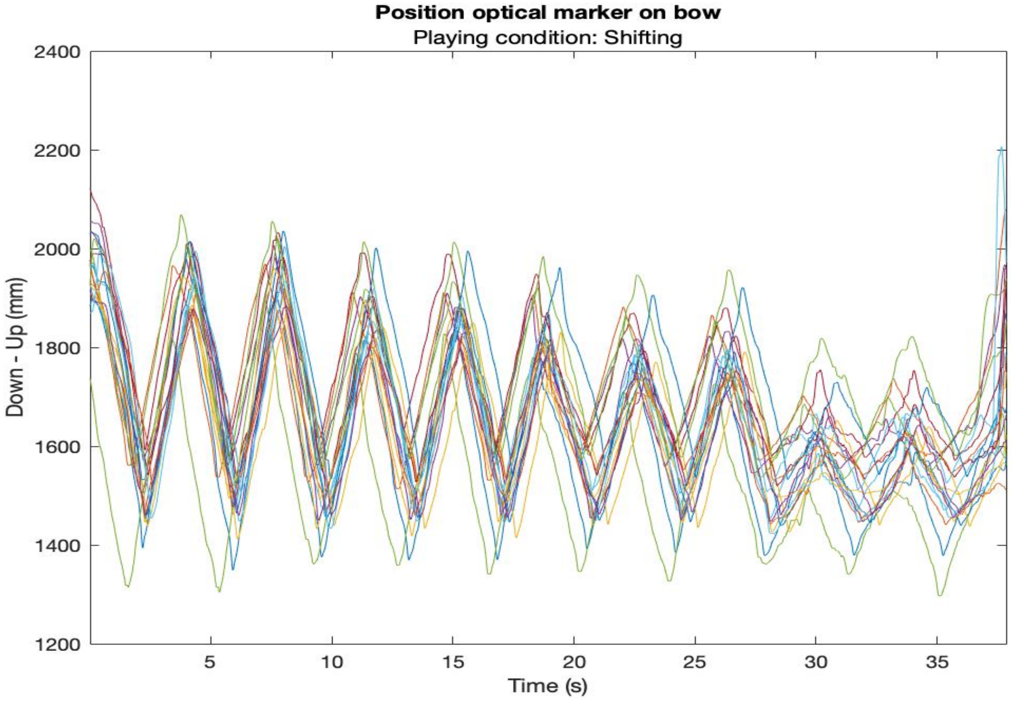

Figure A2. Bowing motions during condition ‘shifting. *Figure shows the upwards motions of the bow during slow bowing and wrist shifting. The motions of the twenty subjects are displayed after dynamic time warping was performed.*

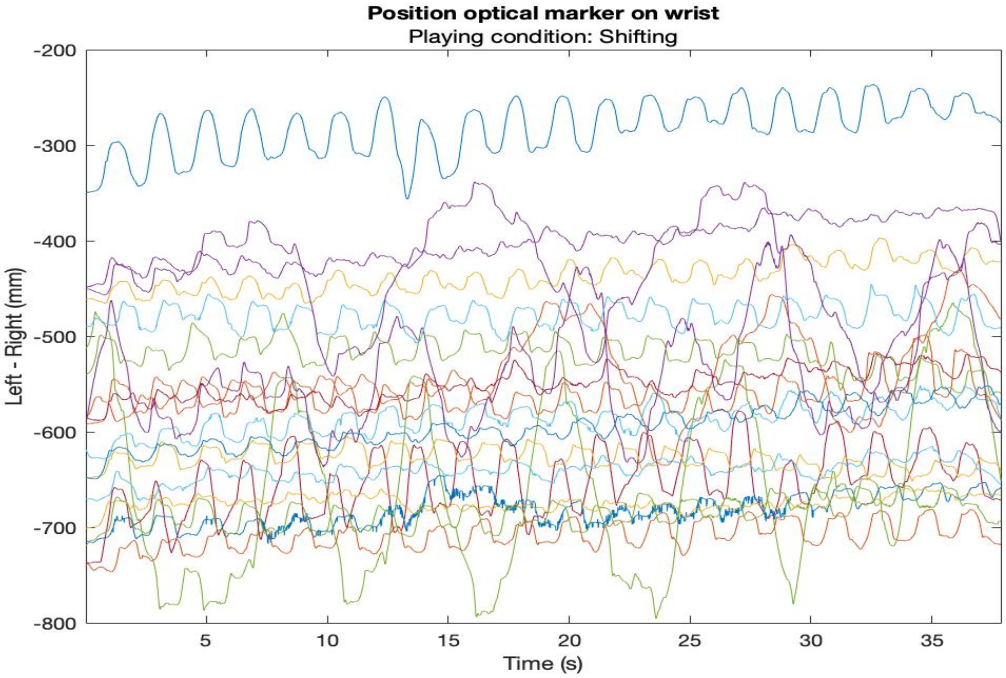

Figure A3. Wrist motions during condition ‘shifting. *Figure shows the sideways motions of the wrist during slow bowing and wrist shifting. The motions of the twenty subjects are displayed after dynamic time warping was performed.*

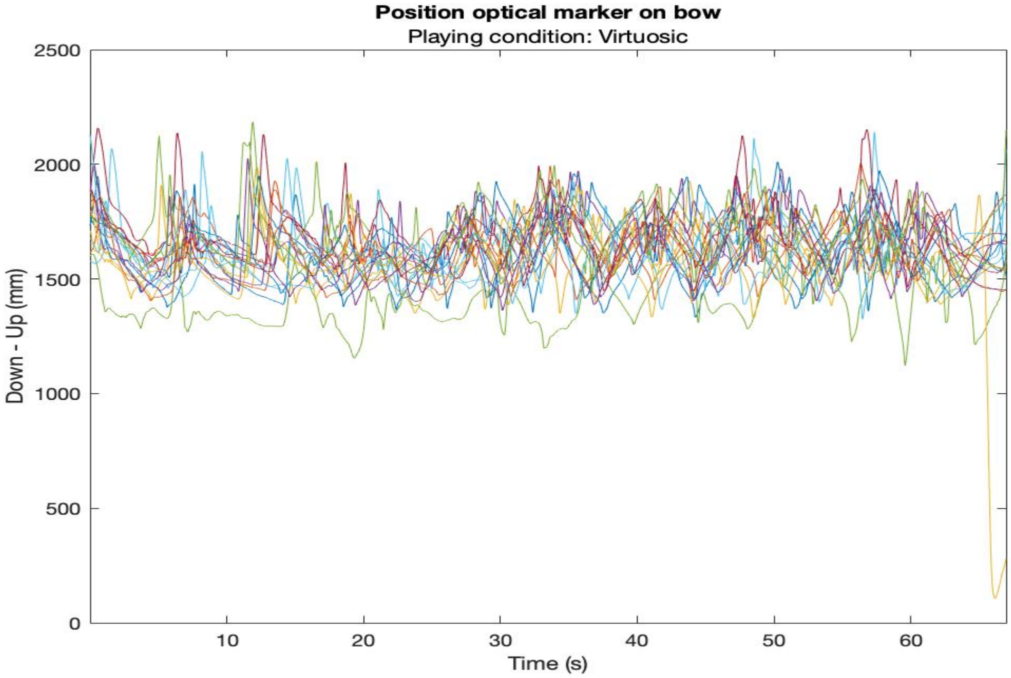

Figure A4. Bowing motions during condition ‘virtuosic. *Figure shows the upwards motions of the bow during virtuosic playing of the twenty subjects after dynamic time warping.*

REFERENCES

Ancillao, A., Savastano, B., Galli, M., & Albertini, G. (2017). Three dimensional motion capture applied to violin playing: A study on feasibility and characterization of the motor strategy. *Computer Methods and Programs in Biomedicine*, *149,* 19-27. http://dx.doi.org/10.1016/j.cmpb.2017.07.005

Andreoni, G., Rigotti, C., Baroni, G., Ferrigno, G., Colford, N.A.T., & Pedotti, A. (2000). Quantitative analysis of neutral body posture in prolonged microgravity*. Gait and Posture ,12,* 235–242. https://doi.org/10.1016/S0966-6362(00)00088-6

Armstrong, T. J., Buckle, P., Fine, J. F., Hagberg, M., Jonsson, B., Kilbom, A., Kuorinka, I. A., Silverstein, B. A., Sjogaard, G., & Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian Journal of Work, Environment and Health, 19,* 73-84*.* https://doi.org/10.5271/sjweh.1494

Bejjani, F. J., Kaye, G. M., & Benham, M. (1996). Musculoskeletal and neuromuscular conditions of instrumental musicians. *Archives of Physical Medicine and Rehabilitation, 77,* 406-413. https://doi.org/10.1016/S0003

Berque, P., & Gray, H. (2002). The influence of neck-shoulder pain on trapezius muscle activity among professional violin and viola players: An electromyographic study. *Medical Problems of Performing Artists*, *17*(2), 68–75.

Buckle, P. W., & Jason Devereux, J. (2002). The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics, 33,* 207-217. https://doi.org/10.1016/S0003-6870(02)00014-5

Chowdhury, R. H., Reaz, M. B. I., Bin Mohd Ali, M. A., Bakar, A. A. A., Chellappan, K., & Chang, T. G. (2013). Surface electromyography signal processing and classification techniques. *Sensors, 13*, 12431-12466. https://doi.org/10.3390/s130912431

Damsgaard, M., Rasmussen, J., Christensen, S.T., Surma, E., & de Zee, M. (2006). Analysis of musculoskeletal systems in the AnyBody Modeling System. *Simulation Modelling Practice and Theory*, *14,* 1100–1111.

Delp, S.L., Anderson, F.C., Arnold, A.S., Loan, P., Habib, A., John, C.T., Guendelamn, E., & Thelen, D.G. (2007). OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement. *IEEE Transactions on Biomedical Engineering, 54,* 1940-1950.

Duprey, S., Michaud, B., Gagne, E., & Begon, M. (2021). Bow influence on violinist gestures: upper arm angles and shoulder muscle activity. FA2020, Forum Acusticum 2020, Dec 2020, Lyon, France. https://hal.archives-ouvertes.fr/hal-03130299

Edmondston, S.J., Sharp, M., Symes, A., Alhabib N., & Allison, G.T. (2011). Changes in mechanical load and extensor muscle activity in the cervico-thoracic spine induced by sitting posture modification. *Ergonomics, 54,* 179-186. https://doi.org/10.1080/00140139.2010.544765

Engquist, K., Orbaek, P., & Jakobsson, K. (2004). Musculoskeletal pain and impact on performance in orchestra musicians and actors. *Medical Problems of Performing Artists*, *19,* 55.

Enoka, R.M., & Duchateau, J. (2015). Inappropriate interpretation of surface EMG signals and muscle fiber characteristics impedes understanding of the control of neuromuscular function. *Journal of Applied Physiology, 119,* 1516-1518. https://doi.org/10.1152/japplphysiol.00280.2015

ErgoCenter at UConn Health Center (2016). Workstation Adjustment Procedures*. UConn Health Center.* https://health.uconn.edu/occupational-environmental/wp-content/uploads/sites/25/2016/01/workstation_adjustment.pdf

Getting Started with Inverse Kinematics (n.d.). Opensim Documentation. https://simtk-confluence.stanford.edu:8443/display/OpenSim/Getting+Started+with+Inverse+Kinematics

Hicks, J.H., Uchida, T.K., Seth, A., Rajagopal, A., & Delp, S.J. (2015). Is my Model Good Enough? Best Practices for Verification and Validation of Musculoskeletal Models and Simulations of Movement. *Journal of Biomechanical Engineering, 137,* 1-24. https://doi.org/10.1115/1.4029304

Hodges, P., van der Hoorn, W., Dawson, A., & Cholewicki, J. (2009). Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. *Journal of Biomechanics, 42*, 61-66. https://doi.org/10.1016/j.jbiomech.2008.10.001

Hodges, P.W., & Tucker, K. (2011). Moving differently in pain: A new theory to explain the adaptation to pain. *Pain, 152,* 90-98.

Hodges, P.W., & Smeets, R.J. (2015). Interaction Between Pain, Movement, and Physical Activity: Short-term Benefits, Long-term Consequences, and Targets for Treatment. *The Clinicƒbal Journal of Pain, 31,* 97-107.

Klein Breteler, M.D., Spoor, C.W., & Van der Helm, F.C.T. (1999). Measuring muscle and joint geometry parameters of a shoulder for modeling purposes. *Journal of Biomechanics, 32,* 1191-1197. https://doi.org/10.1016/S0021-9290(99)00122-0

Kochem, F. B., & Silva, J. G. (2018). Prevalence of Playing-related Musculoskeletal Disorders in String Players: A Systematic Review. *Journal of Manipulative and Physiological Therapeutics, 41,* 540-549. https://doi.org/10.1016/j.jmpt.2018.05.001

Kok, L. M., Haitjema, S., Groenewegen, K. A., & Rietveld, A. B. M. (2016a). The influence of a sudden increase in playing time on playing-related musculoskeletal complaints in high-level amateur musicians in a longitudinalcohort study. *PLoS ONE.* https://doi.org/10.1371/journal.pone.0163472

Kok, L. M., Huisstede, B. M. A., Voorn, V. M. A., Schoones, J. W., & Nelissen, R. G. H. H. (2016b). The occurrence of musculoskeletal complaints among professional musicians: a systematic review. *International Archives of Occupational and Environmental Health*, *89*, 373–396. https://doi.org/10.1007/s00420-015-1090-6

Kok, L. M., Schrijvers, J., & Fiocco, M., van Royen, B., & Harlaar, J. (2019). Use of a Shoulder Rest for Playing the Violin Revisited: An Analysis of the Effect of Shoulder Rest Height on Muscle Activity, Violin Fixation Force, and Player Comfort. *Medical Problems of Performing Artists, 34,* 39-46.

Kok, L. M., Schrijvers, J., Fiocco, M., van Royen, B., & Harlaar, J. (2018). Differences in violin fixation force and muscle activity among violinists with and without complaints of the neck shoulder region. *Journal of Electromyography and Kinesiology*, *43*, 217–225. https://doi.org/10.1016/j.jelekin.2018.11.002

Konrad, P. (2006). The ABC of EMG A Practical Introduction to Kinesiological Electromyography. Noraxon INC. USA.

Larsson, B., Sogaard, K., & Rosendaal, L. (2007). Work related neck–shoulder pain: a review on magnitude, risk factors, biochemical characteristics, clinical picture and preventive interventions. *Best Practice & Research Clinical Rheumatology, 21,* 447-463. https://doi.org/10.1016/j.berh.2007.02.015

Lee, H. S., Park, H. Y., Yoon, J. O., Kim, J. S., Chun, J. M., Aminata, I. W., Cho, W.J., Jeon, I. H. (2013). Musicians' medicine: Musculoskeletal problems in string players. Clinics in Orthopedic Surgery, 5, 155-160. https://doi.org/10.4055/cios.2013.5.3.155

Lund, J.P., Donga, R., Widmer, C.G., & Stohler, C.S. (1991). The pain-adaptation model: A discussion of the relationship between chronic musculoskeletal pain and motor activity. *Canadian Journal of Physiology and Pharmacology, 69*, 683-694.

McInnis, K. C. (2020). Repetitive Strain Injuries. In: Frontera, W. R., Silver, J. K., & Rizzo, T. D. (ed.), *Essentials of Physical Medicine and Rehabilitation* (4th ed.).

Möller, D., Ballenberger, N., Ackermann, B., & Zalpour, C. (2018). Potential relevance of altered muscle activity and fatigue in the development of performance-related musculoskeletal injuries in high string musicians. *Medical Problems of Performing Artists*, *33*(3), 147–155. https://doi.org/10.21091/mppa.2018.3021

Mortensen, J.D., Vasavada, A.N., & Merryweather, A.S. (2018). The inclusion of hyoid muscles improve moment generating capacity and dynamic simulations in musculoskeletal models of the head and neck. *PLoS ONE, 13.* https://doi.org/10.1371/journal.pone.0199912

Neupane,S., Ifthikar Ali, U.T., Mathew, A. (2017). Text Neck Syndrome - Systematic Review. Imperial Journal of Interdisciplinary Research, 3, 141-148.

Nikooyan, A.A., Veeger, H.E.J., Westerhoff, P., Graichen, F., Bergmann, G., Van der Helm, F.C.T. (2010). Validation of the Delft Shoulder and Elbow Model using in-vivo glenohumeral joint contact forces. *Journal of Biomechanics, 43,* 3007-3014.

Obata, S., & Kinoshita, H. (2012). Chin force in violin playing. *European Journal of Applied Physiology*, *112*(6), 2085–2095. https://doi.org/10.1007/s00421-011-2178-7

Okner, M., & Kernozek, T. W. (1997). Chin rest pressure in violin players: Musical repertoire, chin rests, and shoulder pads as possible mediators. *Medical Problems of Performing Artists*, *12,* 112-121.

Park, K. N., Kwon, O. Y., Ha, S. M., Kim, S. J., Choi, H. J., & Weon, J. H. (2012). Comparison of electromyographic activity and range of neck motion in violin students with and without neck pain during playing. *Medical Problems of Performing Artists*, *27*(4), 188–192.

Pataky, T.C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics, 43*, 1976–1982. https://doi.org/10.1016/j.jbiomech.2010.03.008

Philipson, L., Sorbye, R., Larsson, P., Kaladjev, S. (1990). Muscular load levels in performing musicians as monitored by quantitative electromyography. *Medical Problems of Performing Artists, 5,* 79-82.

Punnett, L., & Wegman, D. H. (2004). Work-related musculoskeletal disorders: The epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology, 14,* 13-23. https://doi.org/10.1016/j.jelekin.2003.09.015

Seth, A., Dong, M., Matias, R., & Delp, S.L. (2019). Muscle Contributions to Upper-Extremity Movement and Work From a Musculoskeletal Model of the Human Shoulder. *Frontiers in Neurorobotics, 13.* https://doi.org/10.3389/fnbot.2019.00090

Seth, A., Matias, R., Veloso, A.P., & Delp, S.L. (2016). A Biomechanical Model of the Scapulothoracic Joint to Accurately Capture Scapular Kinematics during Shoulder Movements. *PLoS ONE, 11.* https://doi.org/10.1371/journal.pone.0141028

Seth, A., Hicks J.L., Uchida, T.K., Habib, A., Dembia, C.L., Dunne, J.J., Ong, C.F., DeMers, M.S., Rajagopal, A., Millard, M., Hamner, S.R., Arnold, E.M., Yong, J.R., Lakshmikanth, S.K., Sherman, M.A., Ku, J.P., & Delp, S.L. (2018). OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement. *Plos Computational Biology, 14,* 1-20. https://doi.org/10.1371/journal.pcbi.1006223

Shan, G. B., & Visentin, P. (2003). A quantitative three-dimensional analysis of arm kinematics in violin performance. *Medical Problems of Performing Artists*, *18*(1), 3–10.

Shan, G., Visentin, P., Wooldridge, L., Wang, C., & Connolly, D. (2007). A frequency-based characterization of spiccato bowing in violin performance. *Perceptual and Motor Skills*, *105*, 1027–1051.

Siemelink, I. (2020). *Biomechanical advancements in the development, prevention and treatment of musculoskeletal complaints in high string musicians*. (Unpublished literature review). TU Delft, Netherlands.

Steinmetz, A., Claus, A., Hodges, P. W., & Jull, G. A. (2016). Neck muscle function in violinists/violists with and without neck pain. *Clinical Rheumatology, 35*(4), 1045–1051. https://doi.org/10.1007/s10067-015-3000-4

Stokes, I.A.F., Fox, J.R., & Henry, S.M. (2006). Trunk muscular activation patterns and responses to transient force perturbation in persons with self-reported low back pain. *European Spine Journal, 15,* 658-667.

Tengwall, R., Jackson, J., Kimura, T., Komenda, S., Okada, M., & Preuschoft, H. (1982). Human Posture in Zero Gravity. Current Anthropology, 23, 657-666.

Thelen, D.G., Schultz, A.B., & Ashton-Miller, J.A. (1995). Co-contraction of Lumbar Muscles During the Development of Time-Varying Triaxial Moments. *Journal of Orthopaedic Research, 13,* 390-398

Turner-Stokes, L., & Reid, K. (1999). Three-dimensional motion analysis of upper limb movement in the bowing arm of string-playing musicians. *Clinical Biomechanics, 14*(6), 426–433. https://doi.org/10.1016/s0268-0033(98)00110-7

Visentin, P, & Shan, G. (2003). The Kinetic Characteristics of the Bow Arm During Violin Performance: An Examination of Internal Loads as a Function of Tempo. *Medical Problems of Performing Artists, 18*, 91-97.

Wolf, E. Möller, D, Ballenberger, N., Morisse, K., Zalpour, C. (2019). Marker-Based Method for Analyzing the Three-Dimensional Upper Body Kinematics of Violinists and Violists: Development and Clinical Feasibility. *Medical Problems of Performing Artists, 34,* 179-190.

Wu, G., Van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C, Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics, 38,* 981-992.