Identifying and Evaluating Vocation-Related Neuro-Musculoskeletal Deficiencies in Professional Musicians: A Review

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Abstract: A combination of factors exposes musicians to neuro-musculoskeletal disorders, which lead to pain and damage. These involve overuse due to long playing hours, containing repetitive movements under stressful conditions, usually performed in an unnatural posture. Although the evoked disorders are usually non-traumatic, they may often lead to prolonged or even permanent damage. For instance, in upper string players, these include bursitis and tendinopathies of the shoulder muscles, tendonitis of the rotator cuff, injury at the tendon sheaths, medial or lateral epicondylitis (also known as tennis elbow), myofascial pain, and wrist tendonitis (also known as carpal tunnel syndrome, or De Quervain’s syndrome). In cases of intensive performance, a traumatic injury may result, requiring drastic means of intervention such as surgery. It should be pointed out that the upper body and upper extremities are the most commonly affected sites of playing musicians. This review provides a description of the playing-related motor disorders in performing musicians, and of the methodologies used to identify and evaluate these disorders, particularly for violinists and other upper string players.

Keywords: vocation-related neuro-musculoskeletal disorders; evaluation of playing-related disorders in professional musicians; temporomandibular joint; diagnostics of muscular disorders; biomechanical aspects of neuro-muscular deficiencies

1. Introduction

Vocation-related deficiencies place a burden on the working individual, society and economy, requiring means to identify, evaluate and alleviate the factors responsible for evoking these deficiencies. Specifically, performing music players are exposed to the hazards of neuro-musculoskeletal injuries due to the high loads their body is subjected to, as well as discomfort and pain. It has been reported that among orchestra musicians, the incidences of pain and/or neuro-musculoskeletal disorders (percentages of tested players in a given group of instruments) are 75% for violin and viola players, 73% for cello, 60% for double-bass, 69% for woodwinds, 39% for brass and 32% for percussion players [1]. Players of the violin and viola are thus specifically recognized as the most susceptible to playing-related musculoskeletal disorders (PRMD) [2–8].

In these players, the muscles and joints of the upper extremity are the most frequently affected, particularly on the left side, and the side on which the instrument is actually being held [7,9–11]. The unusual and non-symmetrical postures involved in generating the motion of the upper limb segments have been reported to enhance the formation of PRMD [12]. The neck, shoulder and temporomandibular joint (TMJ) are particularly prone to damage due to the continued flexion of the head and the shoulder required to grip the instrument in place. The limbs and trunk are subject to relatively high loading forces, repetitive movements, vibrations and fatigue, and the elbow and fingers are common sites of disorders [11,13–15]. In addition, upper string musicians perform nearly incessantly during the concert, which makes them even more susceptible to fatigue and injury.
In the following sections, common neuro-musculoskeletal deficiencies are described, alongside the methods used to identify and evaluate the factors responsible for these deficiencies. In Section 2, temporomandibular deficiencies (TMD), which are associated with the TMJ, are described and discussed. The methodologies for assessing the TMD, including imaging, the application of inserts and devices, displacement detection methods, and finite element analysis (FEA) methods, are also presented. Disorders related to the active muscles involved during playing are outlined in Section 3. Methodologies for detecting these muscle disorders, including electrodiagnostic methods, electromyogram (EMG) and EMG applications, follow. Finally, disorders related to body posture, kinematics and dynamics are presented in Section 4. The issues discussed include motion detection and analysis, force and impact, multi-parameter detection and multidimensional analysis, as well as semi-quantitative methods using visual assessment, physical examination and questionnaires.

Table 1 provides an overview summarizing the methods, variables and analyses used for identifying and evaluating vocation-related neuro-musculoskeletal deficiencies in professional musicians.

2. Temporomandibular Joint (TMJ) and Temporomandibular Disorders (TMD)

2.1. The Existence of TMD

Disorders of the TMJ pertain to the musculoskeletal system and are associated with complaints in the orofacial region where the muscles of mastication and/or the TMJ are involved [16,17]. The playing of musical instruments has frequently been linked to the presence of TMJ disorders (TMD).

2.1.1. Wind Instruments

Wind-playing musicians may overload the masticatory system due to straining of the masticatory muscles and facial muscles that control the shape of the stress and lips, leading to discomfort and pain [17–20].

2.1.2. Upper String Instruments

During the playing of upper string instruments such as violin or viola, the instrument is supported between the left shoulder and angle of the jaw to fixate the instrument between the inferior border of the mandible and the shoulder (supraventricular fossa). Further, to better stabilize the instrument with the shoulder, the mandible is rotated towards the chin rest of the instrument. This lateral repositioning of the mandible can be harmful to the masticatory muscles as well as to the TMJ.

With fewer teeth supporting the bite force, articular instability results [3,21,22]. Thus, the masticatory muscles, which operate in combination with the neck muscles and the orofacial skeletal system, become stressed. The myofascial trigger points of the muscles of mastication induce jaw pain [7,23].

In addition, due to the prolonged holding of the instrument between the left supraventricular fossa and the chin, there is a combined effect of pressure on the mandible, chronic excessive forces to the right TMJ, clenching of the muscles of mastication, and vibrations transmitted from the instrument to the jaw [7,24,25]. It should also be noted that in hypermobile upper string players the TMJ often suffers from laxity, which can lead to recurring subluxation of the joint and to interference with proper performance [25–27].

The obvious consequence from the above is the development of an overuse syndrome with myofascial pain dysfunction [28]. Further, due to loss of loading equilibrium and mechanical stress imbalance, articular remodeling becomes destructive in nature, resulting in injury and premature joint degeneration [28–30].
Proclination
The changed balance of muscular activity between tongue and lip, in addition to the pressure of the violin on the chin, results in anterior inclination of the upper and/or lower incisors, known as proclination [31,32].

Occlusion
The previously mentioned mandibular lateral displacement, consisting of a lateral inclination of the occlusal plane and resulting in differences between the right and left masticatory muscles, gives rise to a marked uneven stress distribution in the mandible [33]. The cross-bite malocclusion found in upper string players has been reported as evidence of some TMJ pain, and/or the habit of jaw clicking [22,24,25,28,34,35].

Occlusion may also affect posture [33,36]. Facial morphology, particularly anteroposterior facial skeletal morphology, was reported to correlate with cervical curvature [37–42].

2.1.3. Lower String Instruments
Temporomandibular disorders, often with chronic low back pain, have also been reported in cello playing, due to the forward head posture, accompanied by a posterior thoracic curve and rounded shoulders [43]. The forward head posture may be required in order to look down at the left fingers while playing and for better reading of the music notes [43,44].

2.2. Methodologies for TMD Identification and Evaluation
2.2.1. Imaging Methods
Postero-anterior cephalogram is a radiograph of the head taken with the X-ray beam perpendicular to the patient’s coronal plane, with the X-ray source behind the head and the film cassette in front of the patient’s face [31].

Panoramic tomogram of the jaw, or panoramic radiography, also called panoramic X-ray, is a two-dimensional scanning dental X-ray that captures the entire mouth in a single image, including the teeth, upper and lower jaws, surrounding structures and tissues. It shows a two-dimensional view of a half-circle from ear to ear [31].

Lateral cephalogram is an X-ray taken of the side of the face with very accurate positioning, so that various measurements can be made to determine the relationship of the top and bottom jaw (maxilla and mandible), and therefore assess the nature of a patient’s bite [32].

The above X-ray methods have been used to compare between players, and gender- and age-matched controls. Significant morphological differences have been found between violin players and controls [31,32]. Different parameters have been suggested for characterization and comparison. For instance, in the lateral cephalogram method, six cephalometric parameters are used for comparison [45]:

1. Maxilla angular position with reference to the base of the skull;
2. Mandible angle position with reference to the base of the skull;
3. Facial type. For this parameter, the facial axis, facial angle, mandibular plane, lower facial height and mandibular arch are used to determine one of three face types—dolicho facial, having a disproportionately long face; mesofacial, having an average shaped face, neither too long nor too wide; brachyfacial, having a disproportionately short face;
4. Sagittal skeletal relation [46] or facial convexity as determined by the anteroposterior relationship of the mandible to the maxilla;
5. Upper incisor inclination in relation to the maxilla upper mandibular incisor inclination;
6. Lower incisor inclination in relation to the mandible.

Using these parameters, upper string players are found to have a measurable increase in the facial height compared to the matched controls, especially in the right side of the lower face, and an increase in proclination of the upper and lower incisors [31]. This can be considered to result from prolonged playing of the violin, involving increased face
muscle activity. Thus, compared to controls, the categories of violin and viola players are shown to have a higher prevalence of brachyfacial type individuals, manifested by smaller facial heights and greater lengths of mandibular corpus [31]. This finding has been further confirmed not only for strings, but also for wind instrument players [32].

2.2.2. Inserts and Devices

**Occlusal Contact Insert**

Intra-oral insert devices, fabricated by computerized three-dimensional methods, are used to correct occlusal contact disorders and restore the occlusal stability of upper string players [22]. This is accomplished by taking the dental impression of both teeth arches, a face bow register, and a register of the intermaxillary relation, in the most common playing position. Thermo-moldable materials are used to better individualize the device so as to achieve higher balance of the muscular forces and muscle relaxation. By aiming at full contact of the teeth, teeth grinding can be minimized, and the sensation of occlusal stability while playing can be achieved.

**Chin Rest and Chin Force**

A chin rest [47,48], consisting of a pressure-sensitive pad with shoulder pads as possible mediators [49], is often used in violin playing. Using a sensor mat, the measured quantities, detected at a sampling rate of 50 Hz, include peak pressure, peak force, pressure–time integral, force–time integral, and total contact area utilized over the chin rest during playing. Chin rests may also be used for measuring the compressive force on the left mandible by means of a custom-built force sensor fixed between the violin’s top plate and a chin cup [50]. Using the abovementioned force methods, the maximum voluntary pressing force, as exerted by the chin, averages between the tested subjects at 163 N (SD 39.5 N). The mean chin force for all subjects during the static holding of the violin on the shoulder while being supported by the left hand is found to be 14.8 N (SD 2.8 N). It increases to 21.6 N (SD 5.1 N) with no support from the left hand. The maximum force increases from 16 N under soft playing dynamics to 20 N under strong dynamics, e.g., during performing scales. The force further increases to 29 N with vibrato playing and to 35 N during shifts. Playing tempo and hand position do not affect the force [50].

Changing the chin rest and changing the shoulder pad, both reported to affect the pressure and force applied over the chin rest during violin performance, are common ways to modify the violin to accommodate the player for effectiveness and comfort. Indeed, the use of a rest for the chin and/or a shoulder rest at the correct height can relieve discomfort, even though both devices may increase the weight of the instrument by up to 20% [14,24].

**Displacement Measurements of the Mandible**

Displacement of the mandible accompanied to the exertion of the chin force can be assessed using a digital camera attached to the head of the subject [50]. In brief, still pictures of the incisors are taken while the subject holds the violin and voluntarily applies assigned forces on the chinrest of the violin for approximately 3 s. The deviation of the lower central incisor from that of the upper central incisor is measured from the frame taken. In addition, the angle of attack of the chinrest relative to the line of the teeth estimated from a bar bitten by the molars can also be determined. The lateral and vertical force components on the mandible are determined from the tilting angle of the chinrest relative to the horizontal line of the teeth. The reported lateral displacement of the mandible turns out to be fairly small (<0.4 mm), even with high chin force application, possibly due to clenching of the molars [50].

2.2.3. Finite Element Analysis (FEA) in TMD

FEA can be used to produce three-dimensional models of the entire body to reveal the mandibular stress distribution and displacement of the cervical spine. It is of additional interest to clarify the association between the morphological and functional characteristics of the mandibular deformation and head posture.
Evidently, using a three-dimensional finite element model (3D FEM) of the entire body has confirmed the earlier observations [51] that the occlusal plane in patients with mandibular lateral displacement rises in the direction of the mandibular displacement. The characteristics of mandibular lateral displacement include lateral inclination of the occlusal plane and the differences between the right and left masticatory muscles.

Furthermore, a lateral inclination of the occlusal plane has been found to induce cervical spine displacement and to cause the stress distribution in this area to be asymmetrical, thus affecting posture [52–54]. The simulation of the inclination of the occlusal plane, namely the effect of its lateral upwards inclination, has been carried out by studying the stress distribution in the mandible in conjunction with cervical spine morphology [33]. Here, the mandibular stress distribution and the displacement of the cervical spine serve to simulate masticatory movements and to clarify the association between morphological and functional characteristics and head posture.

With the upward inclination of the occlusal plane towards the mandibular displaced side [51], as well as its lateral inclination [33,52], the FEA model has demonstrated high occlusal stresses on the left side of the mandible, with marked differences in the area corresponding to the left molar root apex. These stresses may induce mandibular deformation associated with bone resorption [29,55]. In the cervical spine, high stress on the right side of the C3–C7 spine level and left displacement are observed, indicating that the lateral inclination of the occlusal plane may contribute to inducing changes both in head posture and mandibular deformation.

The above analysis suggests that in players suffering from mandibular lateral displacement, it is necessary to improve maxillo-mandibular antero-posterior imbalance, as well as to correct the right–left skeletal asymmetry [52].

3. Muscle Activity and Disorders

3.1. Why Disorders May Result from Muscle Activity in Musicians

Playing musical instruments involves the activation of numerous muscles at considerable levels of intensities. Muscle activity is usually monitored by means of the electrical signals accompanying its activity, namely the electroyograpm (EMG). In violin playing, which is essentially an asymmetrical activity, the neck and shoulder muscles hold the instrument in the left side of the body [1]. For instance, the sternocleidomastoid muscle supports the violin whilst the chin undertakes rotation and depression movements [47]. A variety of muscles in the left upper limb, including the trapezius, anterior deltoid, biceps brachii together with its antagonistic triceps, wrist and finger muscles, serve, respectively, to provide firm support for the violin, as well as to stabilize the head and elevated arm, enabling simultaneous elbow supination and flexion and controlling hand and finger motion [56–58].

In the contralateral side, the role of the trapezius includes enabling arching movements with the violin bow [56–58]. Other muscles, particularly the deltoid and biceps, are strongly active in bowing motions [4,59].

The electromyographic activity of these muscles reveals their relative roles in actuating the shoulder and elbow joints [56,58]. Controlling the bowing motion is carried out by the forearm flexor and extensor muscles [1,4,35]. Modification of the body posture, as resulting from imbalances in the neck and shoulder muscles, includes forward shifting of the head, elevation and protraction of the shoulders, and changes in the resting position of the scapula and of the glenoid fossa, the latter provoking pain in the shoulder joint [60]. This imbalance is also the cause of increased stresses in the spine, around the C4, C5 and T4 spine levels [61–63].

3.2. Muscle Electrodiagnostic Methods

3.2.1. Measuring Muscle Activity

The electric activity of muscles, electromyography (EMG), while playing has been used to explore the features of muscle activation under a variety of playing instruments.
and playing conditions, and to identify those muscle groups which are most active and hence most exposed to fatigue, pain and damage. Most published works make use of surface EMG, while intramuscular electrodes are less common, and these studies mainly deal with the muscles of the upper limbs and trunk [64–66]. Quantitative EMG can also be used to study the force intensity in various muscles of playing violinists, including the trapezius, deltoids, biceps and triceps muscles [67,68].

3.2.2. EMG Processing and Reproducibility

The EMG signals of string players are often processed in the time domain, e.g., using the average rectified EMG (AREMG) from different muscles, as detected by surface electrodes [67]. Another method consists of quantifying the EMG amplitude and duration distributions in defined time domains, using the exposure variation analysis (EVA) [57,69,70]. This processing method is based on the simultaneous assessment of amplitude variability, as well as the time period corresponding to the different amplitudes. This method has been successfully used to determine the effectiveness of ergonomic solutions in various assembly workplaces [69].

Rectified EMG signals are also used to study muscle synchronicity among the proximal/distal musculature of the limb by means of cross-correlation analysis [71,72], or among antagonistic muscles to reveal synchronicity and co-contraction in drum players [73].

EMG amplitudes as such have no significance on their own, and cannot be compared to one another unless referenced to some standard measure, such as EMG corresponding to the maximum voluntary contraction (MVC) of the actually measured muscle. Another option is to use as a reference the root mean square value of a 10 s voluntary electrical activity corresponding to 30% of the maximum voluntary contraction (MVC) [69].

It should be noted, however, that true MVC is not always measurable, such as in cases of weakness or other muscle deficiencies, and additional ways of normalizing should be sought [74,75]. For instance, dividing the EMG amplitude by the maximal amplitude value of the measured muscle within the same testing set has been used in children with cerebral palsy [76]. The average rectified EMG may also serve as a basis of normalization, as reported for the upper trapezius muscle of upper string players [77].

The individual reproducibility of EMG has been demonstrated in the trapezius muscle of string players [57]. This suggests that EMG measurements can be used to analyze differences in individual pattern in the course of a musical performance, and to determine the efficacy of alternative ways of playing. Inter-player variability of the trapezius has, however, been reported with greater variability when playing a difficult music piece than when playing an easy one [57,67,77,78].

The processing of the EMG in the frequency domain is associated with the frequency content of the signal, and specific quantities, such as mean and median frequencies, and is used to express fatigue of the muscle [79,80].

3.2.3. EMG using Wire Electrodes

Monitoring the electric activity of muscles may also be achieved with fine wire electrodes, which are inserted into the muscle of interest. This method is characterized by its high specificity and is therefore expected to produce more accurate activity results, compared to the conventional surface measurements. However, because it is invasive, it may cause discomfort and interfere with normal playing [81].

Studies have been conducted to compare shoulder muscle activity patterns during bowing on the cello, as measured by both surface and fine wire EMG. The invasive electrodes are inserted into the supraspinatus, infraspinatus, subscapularis, serratus anterior and lower trapezius muscles of the right shoulder of the subject. In both methods, the results confirm the high levels of contraction of the supraspinatus muscles, and indicate that the fine wire electrodes produce reliable results and do not interfere significantly with the movements and sound production of the tested players [82,83].
3.2.4. Additional Electrodiagnostics Techniques

In addition to EMG, more specific electrodiagnostic techniques can be used in performers. These techniques include upper-limb H-reflex reciprocal inhibition [84], somatosensory evoked potential brain mapping techniques, and transcranial magnetic stimulation (TMS) [65,85], and these have been used particularly in studying focal dystonia and cortical excitability/plasticity. Repetitive TMS is being used for the treatment of complex regional pain syndrome (CRPS), a chronic progressive disease characterized by severe pain combined with sensory, autonomic, and motor disturbances [86].

3.2.5. EMG Applications in Performers

(a) Co-Activation of Muscles

Co-activation (or co-contraction) refers to the simultaneous activity of antagonist muscles. The consequence of co-activation is that the same joint torque can be produced in various different ways, depending on the activation level of each of the acting antagonist muscles [76]. From the purely mechanical aspect, such co-activation is unwanted because, despite the fact that the torque obtained is the same, it can cause a greater resultant joint force. Co-activation is, however, physiologically advantageous because it enhances the controllability of posture and the motion of the joint.

In playing upper string instruments, co-activation takes place when the left forearm, the wrist and the finger flexor, as well as extensor muscles, are used to control the fingering movements in the hand. Similarly, in the right forearm both the flexors and extensors are used to control the bow of the instrument [1,4,35,56]. Co-contraction is also found in drum players at both extremely slow and very high tempi [73]. However, reduced co-contraction is achieved as drum players gain expertise, whereat they tend to display a muscle activation pattern that involves the reciprocal firing of the antagonist flexor/extensor muscles, which improves performance.

(b) Muscle Imbalance and Asymmetry

To reveal muscle imbalance, the quantitative EMG results of the bilateral trapezius, deltoid, biceps, and triceps muscles are compared between players with performance-related pain in the neck and shoulder region and players without pain [35,67]. The EMG activity, as measured by the rectified signal of the pain group of violin players, is reported to be significantly higher in the trapezius (highest), deltoid and biceps muscles on the painful side, indicating that the group suffering from pain employed significantly more force in these muscles when playing, as compared to the pain-free group [47,67].

(c) Risk Assessment (e.g., Increased Deltoid Activity)

Specifically, an increased deltoid muscle activity bears risks due to the following: the deltoid, as the prime abduction mover of arm, is in fact an antagonist muscle of the adduction pectoralis major and latissimus dorsi muscles. Additionally, with raising the arm the deltoid also raises the humeral head. To counterweight the subsequent compression of the humeral head against the undersurface of the acromion and reduce the risk of injury of the supraspinatus tendon, simultaneous contractions of the infraspinatus, teres minor and subscapularis rotator cuff muscles occur [87]. An increased deltoid muscle activity will usually evoke a decrease in subacromial space and an increased compression of the humeral head, thus augmenting the hazard of injuring the supraspinatus tendon.

(d) Subacromial Impingement Syndrome (SAIS)

Subacromial impingement syndrome (SAIS), the commonest disorder of the shoulder, is a painful disorder due to loss of subacromial space [88]. It can be divided into two categories: structural and functional [89]. The first category is characterized by the physical loss of contact in the subacromial space due to inflammation (e.g., of the supraspinatus tendon), or bony growth. In functional impingement, the relative loss of subacromial contact is secondary to the altered scapulohumeral mechanics resulting from glenohumeral instability and muscle imbalance. In players of the violin and viola instruments, a mixture of these two categories takes place [67,90].
(e) Assessment of Shoulder Rest and Backrest Support

EMG of the upper arm muscles of the violin players can also be used to assess the efficacy of a shoulder rest attached to the violin. The EMG signals (rectified EMG) of the left trapezius and right sternocleidomastoid muscles reveal a significant reduction in muscle activity when the shoulder rest is used [62,91]. EMG reduction in these muscles (thus their forces) is associated with their increased lever-arm.

EMG is also an indicator of the efficacy of a backrest support. With the presence of a backrest support, the muscular activity of both left and right erector spinae muscles in both violin and cello players is found to be reduced (about 20% lower) [68].

(f) Comparison Between Upper Strings and Cello Playing

To characterize the asymmetric nature of upper string and cello playing, the spatial distribution of surface EMG of the trapezius and lumbar muscles can be studied. For both upper string and cello groups, the following is found: higher asymmetry of muscle activation in fast compared to slow playing, and a twofold increase in the trapezius muscle activity index (MAI) from the most medial to the most lateral string. In the presence of backrest support, a reduction in the MAI of both left and right erector spinae muscles by about 20% is noticed [68].

Opposed asymmetry differences in the middle and lower trapezius MAI in the upper string and cello groups are also noted between bowing down (from tail to tip) and bowing up (from tip to tail). In upper strings, sliding the bow up requires higher muscle activity (about 50% higher than sliding it down) [56,59]. The reason is that there is a static loading of the left shoulder to support the instrument, and a dynamic, repetitive loading of the right shoulder to facilitate the bowing, the latter being eased by gravity during the bowing down movement [57,68].

Conversely, in cello players, sliding the bow from the tail toward the tip requires higher activity (about 50% higher than sliding it from the tip toward the tail). Here, there is a smaller static load, and the left shoulder has a less supporting role compared to the upper string instruments. In the bowing side, the effect of gravity is less important because the player keeps the bow nearly horizontal throughout playing. Bowing from tip to tail, however, requires dynamic abduction of the right arm, obtained by the elevation of the elbow and depression of the scapula [12,68].

(g) Piriformis Muscle Syndrome

A potential syndrome of great discomfort in cellists is piriformis syndrome, associated with the piriformis muscle, which can particularly become tight and cause pain through pinching of the sciatic nerve [43]. Although a monitoring of the surface EMG of the piriformis is possible [92], it might be preferable to make use of fine-wire electrodes, due to the deep location of the muscle [93].

(h) Muscle Fatigue

Through the processing of the EMG signal, information about muscle fatigue can be obtained both in the time domain (e.g., amplitude of the normalized the rectified signal) and/or in the frequency domain (e.g., median frequency) [79,80]. In musicians, EMG analysis has been found to be efficient for detecting muscle fatigue with PRMD players compared to those without PRMD [94].

(i) Efficacy of “Taping” for Muscle Movement Restriction

As above-described, altering the resting position of the scapula due to muscle imbalance can stimulate pain [60]. This pain can be alleviated by taping the scapulae of violinists into a position that prevents excessive elevation and protraction whilst playing. EMG measurements can be used to evaluate the efficacy of taping treatment by recording the activity from the upper trapezii, the scapula retractor and the right sternocleidomastoid muscles.

(j) Biofeedback

The recording of surface EMG is also useful for biofeedback in the treatment of pain problems, and to train players to reduce excessive force, such as that produced in the left hand and wrist of violinists from gripping the neck of the violin too tightly [24].
EMG feedback has also been shown to reduce muscle tension while playing, by reducing excessive left arm extensor muscle activity in violinists [95].

(k) Assessment of Low Back Pain (LBP)

Using EMG measurements, it has been demonstrated that the presence of low back pain (LBP) can cause a modification of the activation between synergistic muscles of the lumbar back, suggesting that subjects with LBP experience higher fatigability of the erector spinae muscles at the thoracic part than at the lumbar part [96–99]. The increased fatigability of the thoracic part may be relevant in string players whose upper body is active during playing.

It has also been reported that in cases of recurrent low back pain, there is a greater risk of re-injury because of inadequate muscular stabilization of the spine [99]. EMG combined with torque measurements of the erector spinae muscles reveal a direct relationship between LBP history and neuromuscular imbalance [97].

Back pain resulting from prolonged playing in the sitting position has also been associated with the type of chair being used by the musicians [100]. Using high-density surface EMG, it has been suggested that in evaluating different chairs, attention should be focused on the lumbar region, since the higher trapezius, which is directly active in playing, should be left unrestricted. It has been suggested that the use of a saddle chair with a trunk–thigh angle of about 115°, preferably equipped with a lumbar support only, can provide a good compromise between intensity of muscle activation and comfort.

4. Posture and Motion

4.1. Significance of Posture and Movement to Playing Disorders

The analysis of motion kinematics and dynamics is an important tool to assess and characterize the neuro-muscular database of playing musicians under able-bodied and injured conditions. For instance, the kinematics of playing cellists have been measured for assessing the range of motion of the right shoulder, namely, flexion and abduction, and for evaluating the effect of intervention protocols aimed at minimizing the risk of injury [101,102]. Likewise, information about kinematics can be used for developing efficient and effective strategies to prevent overuse syndrome in violinists, keeping biological loads under physiological limits, focusing on physical economy for minimizing fatigue during training [103,104] and for the assessment of postural flaws [6,60,105,106].

4.2. Measuring Kinematics and Dynamics in Playing

4.2.1. Three-Dimensional Motion Analysis

Monitoring the kinematics of the body, violin and bow is accomplished by measuring the time-position of properly attached passive markers using an optoelectronic motion capture system [48]. In 3D motion investigations of the bowing arm of string musicians, single-player reproducibility in repeated testing has been described, versus noticeable differences between players [101,107].

The specific systems include the following:

1. MacReflex 3D analysis system for the analysis of bowing arm movements, including determination of marker positioning, locating of the musician within the calibrated area and standardized bowing exercises. This procedure can also be used to differentiate between instruments, bowing technique and individual differences [15,107].

2. A Vicon multiple-camera motion capture system, for quantitative kinematic description of the motions of the arms and violin bow, is being used for motion analysis in violin performance and control skills using all four strings [15,58,108]. Data analysis makes use of quantitative model comparison and statistical analysis. The three-dimensional time coordinate data are offline reconstructed using a Butterworth filter [56,109].

Angular information can also be obtained from these photogrammetric data [110]. Dynamic modeling using inverse dynamic analysis is used to estimate internal loads at the joints [108,111]. This allows one to examine the internal loads of the bow arm during the
enactment of a smooth (legato) bowing technique at a variety of playing speeds (tempi). The synchronization of this system with sound further allows one to better correlate motion input with quality of performance [111]. A slightly different Vicon system, consisting of four specialized cameras emitting infrared strobes, reflecting back from markers (placed on left fingers, bow, and violin) to the camera lenses, allows one to study whether position and string changes may influence bowing-fingering (right–left) coordination [15,112].

4.2.2. Electrogoniometers (Twin Axis) and Potentiometers (Single Axis)

Angle measurements of joint mobility provide objective data for musicians with clinical symptoms, and information about whether these data contribute to the prevention of performance-related disorders. Thus, bi-axial electrogoniometers are used to measure the range of wrist motion, to identify frequently assumed wrist positions, and to determine the differences between right and left wrist motions among professional violinists [113,114]. Twin-axis electrogoniometers are also used to measure radial/ulnar postural changes of violin players, and the software used with the equipment provides a count of the repetitions [11].

Single-axis potentiometers are used to measure finger movement in double bass players [15,115].

4.2.3. Impact Loading

Intensive, stressful activations of the upper limb during playing result in severe loading on the upper limb from each bowing beat, and are related to progressively increasing harm. The small intrinsic hand muscles, which are greatly involved in generating these recurrent abrupt movements, are thus exposed to risk of damage [116,117]. Similar to the muscles, tendons and nerves of the wrist, the forearm, elbow, shoulder, and neck are at great risk, and repetitive strain injury can take place [13].

Muscles are also capable of shielding the bones and joints from injury by the dampening of the impacting forces, and muscle fatigue may hinder this function [80,118–122]. An example to illustrate this effect is the developing fatigue of the leg muscles in running, followed by a rise in impact loading on the shank bone, with greater high-frequency joint-damaging loads [8,80,123–125]. While information about muscle fatigue is obtainable from the above-mentioned EMG measurements, dynamic or impact loading can be specifically monitored by use of accelerometers.

4.2.4. Accelerometry

The application of accelerometers to measure movement, especially dynamic movement, can provide detailed information about abrupt dynamic loading, including intensity, timing and frequency content [80]. Although the application of accelerometers in assessing musicians’ movement has up to this point been limited, the potential of this method is promising [126–128].

4.2.5. Other Force Measurements and Dynamometry

Forceplate Measurements

Forceplate measurements can be used to monitor the foot–ground reaction forces during playing. For instance, in flute playing, two forceplates, one for each foot, can serve to study the shifting effects from one foot to the other following changes in playing technique [102]. Forceplate measurements, together with kinematic and EMG measurements, may also be incorporated into a multi-segment biomechanical model for studying the biomechanics of violin playing [58].

Other force and pressure measurements include chin force in violin players, as above-described in Section 2.2.2.

Finger–Fingerboard Force

A custom-designed force transducer has been used to monitor the force exerted on the fingerboard of the instrument by the left finger in playing a musical note at diverse
playing tempi or other playing conditions [129,130]. Force exertion usually comprises two distinct time-stages: (a) pressing the string to overcome its tension until contact with the fingerboard is achieved; (b) increasing the force during contact to stabilize the string in a position corresponding to the desired musical note.

The reported results for the finger force values have ranged from 4.5 N at low tempi (less than 2 Hz) to 1.7N at high tempi (more than 2 Hz). Of all the fingers’ forces, the highest is in the index finger, with a lower intensity at softer dynamic levels of the tone [129].

**Finger Model**

The above finger force has been used as the input force in a 3D biomechanical dynamic model for the index finger, to simulate the internal tendon and joint forces of the hand. Model results using this model have yielded tendon forces around 5 N, and joint forces around 8 N [131,132].

**Table 1.** Summary of methods, variables and analyses used for identifying and evaluating vocation-related neuromusculoskeletal deficiencies in professional musicians (abbreviations used: TMJ = temporo mandibular joint; Post-ant = postero-anterior; EMG = electromyogram; SAIS = subacromial impingement syndrome; TMS = transcranial magnetic stimulation; LBP = low back pain).

| Disorder Addressed | Methods, Variables and Analysis [Refs] | Musical Instrument |
|--------------------|----------------------------------------|--------------------|
| **TMJ**            | Non-specific methods [17–20,31]         | Human voice, winds, strings |
| Specific methods:  | Post-ant cephalogram and               | Upper strings      |
| panographic        | panoramic tomograms [18,31]            |                    |
| cephalogram        | Lateral cephalogram [32]               |                    |
| Intra-oral device  | [22]                                   |                    |
| Chin-rest [47–50]  | Displacement measurements [50]         |                    |
| FEA [51]           | **Muscle Activity**                    |                    |
| EMG (surface) [64–66]: Average rectified [67] |                      |                    |
| Exposure variation analysis [57,69,70] | Signal variability [57,67,77,78] | |
| Co-contraction [35,56,73,76] | Synchronicity [71–73] | |
| Imbalance and asymmetry [67] | Risk assessment [87] | |
| SAIS [67,90]       | Shoulder and chin rest [62,91]         | Upper strings, percussion, cello |
| Comparison with cello [56,57,59,68] | Piriformis muscle syndrome [43,93] | |
| Fatigue [94]       | Efficacy of “taping” [60]              |                    |
| Biofeedback [24,95] | LBP [96–100]                           |                    |
| EMG (wires) [81–83] | Possible interference with playing      |                    |
| H-reflex [84]      | Somatosensory evoked potential [65,85] |                    |
| TMS [86]           | **Posture and Motion**                | Upper strings, cello, bass |
| Kinematics:        | Motion analysis [48,101,107], MacReflex [15], | |
| Vicon [108,109]    | Photogrammetric data with inverse dynamics [108,111] | |
| Electrogoniometers [113,114], | Potentiometers [15,115] | |

Table 1. Summary of methods, variables and analyses used for identifying and evaluating vocation-related neuromusculoskeletal deficiencies in professional musicians (abbreviations used: TMJ = temporo mandibular joint; Post-ant = postero-anterior; EMG = electromyogram; SAIS = subacromial impingement syndrome; TMS = transcranial magnetic stimulation; LBP = low back pain).
Table 1. Cont.

| Disorder Addressed | Methods, Variables and Analysis [Refs] | Musical Instrument |
|--------------------|----------------------------------------|--------------------|
|                    | Accelerometry and impact [80,126,128]  |                    |
|                    | Dynamometry:                           |                    |
|                    | Forceplate [58,102]                    |                    |
|                    | Finger force [129,130]                 |                    |
|                    | Flute, violin                          |                    |
|                    | Combined methods:                      |                    |
|                    | EMG + kinematics, dynamics [70,81,111] |                    |
|                    | EMG + acoustics [133]                  | Violin             |
|                    | Multidimensional signal analysis [47,56,59,70] |                    |
| General            | Semi-quantitative:                    | Upper strings, cello, bass, keyboard, harp, percussion |
|                    | Visual assessment, physical examination, questionnaire [2,7,60,106,134] |         |

4.3. Combined Measurements

4.3.1. EMG and Kinematics/Dynamics

Combined measurements of kinematics of the bowing arm and of the EMG of the trapezius and serratus muscles are performed to look for differences between violinists with subacromial impingement syndrome (SIS) and uninjured violinists [70,81,111]. The SIS violinists have been found to have the following features: (a) shorter trapezius activity, as well as greater and longer-lasting posterior scapular tilting, upward scapular rotation and internal scapular rotation; (b) smaller amount of flexion of the glenohumeral joint and greater amount of external rotation; (c) consistency of these kinematical changes with the recruitment pattern of the serratus anterior and upper trapezius.

4.3.2. EMG and Acoustic Signals (Sound)

The simultaneous recording of muscle activity and its relationship to sound production as captured by its acoustic signals can be used to study a musical performance of violin playing with vibrato. Muscle activity is expressed by EMG, and the muscles measured, all from the left upper limb, include the clavicular portion of the deltoid, biceps brachii, flexor and extensor digitorum, and pronator teres [133].

4.4. Multidimensional Signal Analysis (MSA)

Multidimensional signal analysis (MSA) involves the coordination and correlation between data collected through multiple experimental and analytic techniques. For complex biosystems, MSA permits the integration of several observational perspectives, and provides a better means to investigate features of the system that cannot be easily understood by using one method only [59]. Thus, by integrating EMG, kinematics and dynamic measurements, and using inverse dynamic modeling, information about internal loading in muscles and joints can be obtained in different playing conditions [47,56,58,59,70,101,107].

4.5. Semi-Quantitative Methods Using Visual Assessment, Physical Examination and Questionnaire

Task-specific measures of PRMD, incorporated into qualitative posture assessment and physical examination, have been used in conjunction with questionnaires [2,7,60,106,134]. The common studied areas have included pain complaints, instrument playing habits, location of pain, playing experience, and length of daily practice [13].

Questionnaires are also being used in problems related to temporo mandibular disorders (TMD) and craniomandibular dysfunction (CMD) [20]. Since CMD is related to increased muscular load in the muscles of mastication, as well as the trapezius and sternocleidomastoid muscles, CMD questionnaires may be supplemented with EMG measurements [135].
5. Summary

This review provides a description of the playing-related motor disorders in performing musicians, and of the methodologies used to identify and evaluate these disorders. The muscles and joints of the upper extremities of music players are the most frequently affected. The unusual and non-symmetrical postures involved in generating the motion of the upper limb segments enhance the development of PRMD. Typical sites of disorders include the TMJ, neck, shoulder, elbow, wrist and fingers. The limbs and trunk are also subject to relatively high loading forces, repetitive movements, vibrations and fatigue. Methodologies to diagnose, characterize and evaluate PRMD are thus clearly of importance for the further improvement of devices and techniques aimed at reducing damage associated with the prolonged playing of music.

6. Recommendations for Future Research

The problem of vocation-related neuro-musculoskeletal deficiencies in professional musicians is multidisciplinary in nature. Thus, a basic recommendation for future work relates to the importance of combining reliable data from both the descriptive–qualitative and quantitative sides, as well as to the provision of appropriate tools for the synthesis and analysis of these data. More specific recommendations for future work include:

1. Development of biomechanical modeling of the human body–musical instrument complex, which would allow the quantitative formulation of motion and internal torques and forces within the joints, muscles and tendons. The developed model should rely on anthropometric data and on actual measurements acquired during playing;

2. The refinement of kinematic measurements should include the reduction of errors due to the inaccurate positioning of markers on both the body and instrument. Information about peak impulsive forces can be acquired via the usage of accelerometers; these could provide significant information about exposure to repetitive strain injuries during playing.

EMG measurements should be more widely performed as they provide both qualitative and quantitative information, the latter being useful as a model input. In that respect, fine-wire EMG, which was shown not to interfere with normal playing, offers the advantages of better specificity and the capacity for deeper muscle measurements.

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