THE ROLE OF BIOMECHANICAL PARAMETERS IN UPPER-EXTREMITY MUSCULOSKELETAL PAIN EXPERIENCED BY TROMBONISTS

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ABSTRACT

There is a paucity of scientific and pedagogical literature regarding biomechanical factors, including posture, balance and musculoskeletal kinetics, in trombonists. Few published guides address posture, most doing so in superficial manner, offering direction on holding the instrument, hand position and instrument angle, without evidence base. Low brass players report a significant prevalence of playing-related musculoskeletal problems, with left upper extremity pain frequently reported. A body of literature is evolving which explores biomechanical parameter significance in players of string and keyboard instruments, but present literature regarding this in trombonists has been limited primarily to electromyography (EMG). This study sought to establish and compare the relevance and validity of motion-capture, EMG and ground reaction force simultaneous measurement methodology in trombone players. Biomechanical parameters demonstrating higher inter-subject variability are outlined, with the goal of establishing the more relevant measures and a more-streamlined methodology for future biomechanical study of this population. Deviation from biomechanical norms is evaluated as a potential risk factor for pain.

Keywords: musician, posture, balance, musculoskeletal, biomechanics, EMG

CONTRIBUTIONS OF AUTHORS

Research and writing in all sections of this thesis was conducted by Ron Garnett.

Additional contributions:

Chapter 2 – Are Factors of Posture and Balance Integrated in Research Studies on Upper Extremity Musculoskeletal Pain in Instrumental Musicians? A Scoping Review

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LIST OF ABBREVIATIONS

AT – Alexander Technique
CoP – Center of Pressure
EMG – Electromyogram
GRF – Ground reaction force
LUE – Left upper extremity
MeSH – Medical subject headings
MPPA – Medical Problems of Performing Artists (Journal)
MSK - Musculoskeletal
MVC – Maximum voluntary contraction
PRISMA-ScR – Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Scoping Review)
PRMD – playing-related musculoskeletal disorder
RCT – Randomized controlled trial

CHAPTER 1: INTRODUCTION

This study seeks to establish and compare the relevance and validity of multiple biomechanical parameters, including motion-capture, ground reaction force (GRF), and electromyography (EMG), in the determination of biomechanical variability as a risk factor for pain in trombone players. Improved and consistent prevention strategy in pedagogy, and more effective treatment strategy for health care disciplines is the anticipated value. All phases of this work involved inter-disciplinary collaboration between representatives of sport medicine, music performance/pedagogy, and kinesiology at the University of Lethbridge.

There is a paucity of scientific and pedagogical literature regarding biomechanical factors, including posture, balance and musculoskeletal kinetics, in this population. Few published guides address posture, most doing so in superficial manner, offering direction on holding the instrument, hand position and instrument angle, without evidence base. A number of references located via Medline, Web of Science and Sportdiscus indicate that low brass players experience significant degrees of playing-related musculoskeletal problems, with left upper extremity (LUE) pain frequently reported. Common knowledge among low brass faculty is that the few published guides on low brass instruction which mention posture consideration, do so only in superficial instructional manner.

Wallace et al. (2016) [1], describes the University of North Texas Trombone Health Survey in which 76% of respondents indicated trombone-related pain in the year prior. Blanco-Piñeiro et al. (2016) [2] explored the literature for a relationship between posture and musculoskeletal health in instrumental musicians, the resulting review indicative of growing interest but varying study designs and parameters. Postural awareness techniques such as body mapping, Feldenkrais [3] and the Alexander Technique (AT) [4] are often promoted in instrumental music education (Williamon and Buckoke, 2007) [5]. Musicians bearing an instrument's weight, while also engaging upper extremity motion in playing (particularly string and trombone), experience a shifting center of gravity. The quality and mechanism of balance compensation may be a determinant in musculoskeletal stress.

It was postulated that an evaluation of multiple biomechanical factors, particularly those which describe LUE weight-bearing and torque forces created by the shifting centre of gravity, and the adjustments required to accommodate that shifting, could improve the understanding of determinants in playing-related pain, and provide direction for preferable and standardized methodology and parameter use in future research.

The initial step was to explore current knowledge of any relationship between general instrumental musicians' playing-related musculoskeletal pain, and posture. A scoping literature review, recently updated to include publications to October 2021, is reported in Chapter 2 of this document. The search strategy utilized medical subject heading (MeSH) terms and keywords in three broad areas: pain, music and postural balance. Output from the search of three databases was uploaded to Endnote, scanned for duplicates, the studies then evaluated according to predefined eligibility criteria. Few randomized controlled trials (RCTs) in this area of study were found, with a general lack of standardization and validation of biomechanical parameters utilized; most contributory studies were cross-sectional, case-control, or cohort in nature.

Further chapters are based on successive separate research studies, each with an independent research protocol. While there is overlap in the biomechanical tools used, each phase involved iterative but independent methodology to address evolving research questions regarding biomechanical applicability. Each chapter therefore has a methods section.

As described in Chapter 3, to explore the feasibility of potential technology options available for the study of motion, posture, and balance in trombonists, a proof-of-concept trial establishing trombone-specific methodology, was conducted in the University of Lethbridge motion-capture lab. An effective model and protocol, generating data for GRF and multi-segment body position data during slide motion, was developed. The Vicon Nexus 1.7.1 technology [8] was tested for segment recording of the human trombonist subject, pre-existing models having established utility in the study of sport-activity motion, and in musicians playing string instruments. No adjustment of these human-subject models was required for trombone performance. A proposal for marker placement for the trombone instrument had however not been previously published, so required local model development. Trials of data collection discovered that optimization of camera placement and dark cloth covering of the bell portion of the instrument were required to avoid spurious infrared reflections and marker “ghosting” from the metallic instrument. The integration of a ground reaction force (GRF) plate for each foot of the standing musician required calibration for appropriate sensitivity to balance force in this scenario. This phase of study established protocol for the reliable simultaneous collection of motion-capture and ground-reaction force over a short (approximately 10 second) period of etude performance. The demonstrated joint excursion confirmed the LUE as subject to primarily static loading with the right side featuring more dynamic activity. This laterality asymmetry, may be complementary to prior reporting from Chesky (2002) [6], in which problems of the left arm were noted to be twice as common as the right in trombonists. Parallels are noted to the relative risk patterns for static versus dynamic activity in violinists, as previously noted by Visentin (2004) [7].

Left arm static load was postulated as a pain contributor. While motion capture outlines joint angles, this alone does not fully reflect the degree of muscle load and activity. A second proof-of-concept study was performed, adding simultaneously collected EMG measures of key muscle groups of the LUE to the motion-capture and ground-reaction force data-collection protocol, for a single trombonist subject. As described in Chapter 4, utility of the EMG technology and methodology verification for the simultaneous generation of relevant data while playing was confirmed. Data indicated that left shoulder angles were near-static, with LUE EMG also indicating static activity without variability relationship to slide motion. GRF, however, found variability mostly in lateral balance shifts, corresponding to slide extension.

It became clear that multiple-participant study was necessary to assess for general biomechanical characteristics and degree of variability in playing and bearing the weight of this asymmetric instrument. Evaluation for a relationship between balance tendencies, anticipatory adjustments, and playing-related pain was proposed, in addition to establishing norms for biomechanical parameters in joint angles and EMG activity. The comparison of such parameters for players with differing genders, anthropometrics and ages, and determination if deviation from those norms is a risk factor for the development of pain, was considered in planning. To guide the development of precedent and simplified standardized-approach for future biomechanical studies in trombonists, assessment of the various modalities for significance and relative predictive value was an over-arching theme. The resulting study, extending the methodology verification to a multiple subject setting, is described in Chapter 5.

Utilizing the simultaneous recording of data for multiple parameters, via technology methodology as previously outlined (per Chapter 4), seven university-level trombonists each played a standardized etude. There were multiple new components in this (Chapter 5) phase of study. This included centre of pressure (CoP) evaluation, leading to calculation of Body Swing, allowing comparison between players for postural side-dominance, and quantity of postural adjustment activity. Additionally, each player performed under varying playing "conditions" including seated vs standing posture, legato vs detached playing style, and use of valve as an alternative to 6th slide position. This phase also introduced player pain history as a potential dependent variable in the assessment of biomechanical factors.

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Are Factors of Posture and Balance Integrated in Research Studies on Upper Extremity Musculoskeletal Pain in Instrumental Musicians?: A Scoping Review

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ABSTRACT

It is widely believed that posture and balance stressors are factors in playing-related pain for musicians using hand-held musical instruments. The purpose of this scoping review was to assess the available literature relative to the effects of posture and balance in musicians with neuromusculoskeletal injuries. A search of Medline, Web of Science and SportDiscus seeking articles combining posture and balance considerations with pain in performing artists was performed. From 1,403 articles initially identified by the search parameters, the further abstract/title review for relevance and inclusiveness of pain and posture/balance variables in performing artists resulted in the retention of 29 articles for this full text scoping review. The full-text analysis assessed publication type, study design, participant population, methodology, statistical methods, main results and whether the study evaluated the relationship between posture/balance and pain in musicians.

Overall, the majority of studies including musicians were observational or descriptive. Although, in the last three years, there has been an increase in the number of interventional studies regarding posture, balance and pain in musicians, there is still minimal evidence about the contribution of posture and balance characteristics to pain in musician performers. To reliably establish a predictable relationship with injury symptomatology experienced by musicians, it is essential to integrate standardized, validated measurements of posture and balance in all musicians who report to a health professional with neuromusculoskeletal pain. This will not only allow researchers to determine the effect of postural righting dysfunction on neuromusculoskeletal injuries in musicians, but also may provide a foundation for clinicians to develop effective interventions.

Keywords: musician, posture, balance, musculoskeletal pain

INTRODUCTION

There is a paucity of scientifically-based pedagogical literature regarding biomechanical factors, such as the optimization of posture and balance, in instrumental musicians. For most instruments, the published guides addressing posture in musicians, do so in a superficial manner. The guidelines typically offer direction on hand and instrument position, without evidence of effectiveness.

Musicians simultaneously bearing an instrument's weight and engaging asymmetric upper extremity motion in playing (particularly violin/viola and trombone), experience differential static and dynamic postural balancing forces from the shifting center of gravity. The mechanism and quality of balance compensation strategies may be a determinant in musculoskeletal pain development. Instrumental music education often promotes postural awareness techniques such as centering the force of gravity, body mapping, and engaging yoga, Feldenkrais [53] and Alexander Techniques [21]. In this scoping review, we explore current literature support for the assumption that balance and posture alterations could pose a risk factor for pain in instrumental music performers. In addition, this scoping review assessed the potential benefit for postural awareness instruction and remediation.

The scope for this review included the integration of reports involving players of all hand-held orchestral instruments with playing-related musculoskeletal pain. Concepts and principles learned from this larger population may establish study and investigation templates and guidelines for subsequent research regarding the biomechanical factors putting musicians at risk for chronic pain. A better understanding of the contributions of balance and posture and musculoskeletal pain in musicians not only has the potential for improved teaching but also may guide health provider practices and contribute to more effective prevention in pedagogy and clinical treatment.

BACKGROUND

Musicians and Risk

As noted by Munte et al. (2002)[1], professional level music performance may be among the most complex of human fine motor activities. For example, some segments in the 6th piano etude of Grandes études de Paganini, S.141 (Liszt, Franz), require the bilateral coordination and production of 1,800 notes per minute. In another study, evaluation of average accumulated hours of playing-time rehearsal by age 18, at an elite music academy by the best violin students, was 7,410 hours (Ericsson et al., 1993)[2]. The documented vulnerability of musicians to pain and overuse symptoms was consistent with these extremes of musculoskeletal demand. Pascarelli and Yu-Pin (2001)[3] noted that 28% of patients presenting to an occupational medicine clinic with upper extremity pain, were musicians. A further report by Baadjou et al. [4] indicated that up to 87% of professional musicians experienced work-related complaints of the musculoskeletal system during their careers.

In a systematic review regarding the occurrence of musculoskeletal complaints in professional musicians, Kok et al. (2016)[5] describe a search strategy locating over 1,000 publications, with 21 articles (describing 5,424 musicians) selected for full-text review. Data indicated point prevalence for musculoskeletal complaints ranging between 9 and 68%. The 12-month prevalence ranged between 41 to 93%, and lifetime prevalence ranged between 62 to 93%. Most studies found a higher prevalence of musculoskeletal complaints among women. Brass instrumentalists were reported to have lower rates of musculoskeletal pain than other instrumental groups. Overall, the anatomic areas most affected included the neck and shoulders.

Students appear to be prone to injury. Miller et al. (2002)[6] noted in a study of music students, that while upper limb pain showed no relationship to morphological variation, it did relate to the number of years playing the instrument, and to the duration of practice periods. In a study of university students, Steinmetz et al. (2012)[7] noted twice as much musculoskeletal dysfunction in music students compared to a non-music control group. An earlier study by Roach et al. (1994)[8] reported university student instrumental musicians were twice as likely to have upper-body pain in the shoulder, elbow, and wrist compared to non-musicians but 50% less likely to have lower-body pain. Ioannou et al. (2018)[9] further noted that two-thirds of music students seeking medical care did so because of playing-related pain. Most students experienced an onset of musculoskeletal pain during their first year of university-level studies. Sixty-nine percent of the students experienced acute rather than chronic pain.

Injuries

A common term in reports describing playing-related pain is "performance-related musculoskeletal disorders" (PRMD). Ackermann and Driscoll (2010)[10] described an accepted definition of PRMD as "any pain, weakness, numbness, tingling, or other physical symptoms that interfered with your ability to play your instrument at the level to which you were accustomed". The definition excludes mild transient aches or pains.

Lederman (2003)[11] noted that in a series of over 1,000 instrumentalists evaluated in his medical practice, musculoskeletal disorders were the main concern in 64%, with peripheral nerve problems in 20%, and focal dystonia in 8%. Specific anatomic diagnoses including tendinitis and sprain were less common. Each instrumental group showed characteristic symptoms, presumed to reflect the static and dynamic stresses associated with playing that specific instrument.

Instruments

In a study of upper limb PRMD in professional classical musicians, Kaufman-Cohen and Ratzon (2011)[12] noted higher symptom scores in string musicians versus woodwind and brass players. Regression analyses found biomechanical risk factors, physical environment risk factors, instrument weight, and average playing hours per week, as predictors for upper limb problems.

In brass instrumentalists, Chesky et al.(2002)[13] noted an overall prevalence for musculoskeletal problems of 61%, with the trombone group the highest (70%), followed by French horn and low brass (62%), and trumpet (53%). In trombonists, left upper extremity (LUE) problems were prominent, with left shoulder at 23%, left hand 21%, and left wrist 20%. An open survey of 316 trombonists by Wallace et al. (2016)[14] noted that 77% of the trombonists reported playing-related pain in the year prior.

Posture

Ackermann and Adams (2004)[15] note a high agreement between injured violinists/violists and health care providers regarding the rankings in the perceived causes of injury. Poor posture was among the most prominent risk factors for injury listed by both groups. The authors further indicated that instrumental instructional books and papers on posture and techniques reported instructor personal views and experiences rather than scientific data regarding injury.

Hand-held instruments involve weight-bearing and movement vectors with complex static and dynamic musculoskeletal loads. Many instruments produce an uneven weight distribution and playing workload between the upper extremities. Playing an instrument with asymmetry has been found to be an additional risk factor for developing sub-optimal postures (Ramella et al., 2014)[16].

Problems of posture may extend beyond playing-time alone. Postural stabilization system defects were found in 93% of 84 musicians attending a specialized clinic (Steinmetz et al., 2010)[17]. Over half of those displaying postural faults occurred when sitting or standing (Blanco-Piñeiro et al., 2015)[18] even without instruments in hands. Cyganska et al. (2017)[19] noted that in children, persistent changes of body posture in violin-playing led to early musculoskeletal complaints. These findings indicate the need for further research regarding prevention.

Posture research has tended toward a descriptive focus on biomechanics. There has been less emphasis on musicians' perspectives, including postural impact on movement and performance quality (Blanco-Piñeiro et al. 2017)[20]. Maintaining stable alignment and a balanced support base, while still allowing necessary mobility, is considered desirable (Blanco-Piñeiro et al. 2015)[18]. A theory combining posture concepts of both musicians and health professionals, might facilitate a unified approach to posture management.

A literature review by Blanco-Pineiro et al.(2017)[20] considered the relationship between playing posture and PRMDs. This review concluded that despite strong interest, the empirical data in most studies created academic limitations. Prior work, whether health-focused or performance-focused, showed methodological weakness. The review of 42 studies of postural influence on health and performance published between 1972 and 2012, noted a variety of strategic weaknesses including small sample sizes, large heterogeneity of musician ages/instrument played/musical level achieved, as well as heterogeneity of tools and procedures used to evaluate posture. Many studies did not even specify how posture was assessed. The authors indicated a need for higher methodological rigor in posture evaluation to promote reliability and validity of the resulting observations.

Prevention

With musculoskeletal disorders and performance anxiety common in musicians, many practice the Alexander Technique (AT) [25], a psycho-physical method claimed to release unnecessary muscle tension and inhibit unproductive habitual muscle activity. Klein et al. (2014)[21] presented a systematic review, with a variety of outcome measures assessing the effectiveness of AT sessions in musicians. Randomized controlled trials and controlled non-randomized trials suggest that AT may improve performance anxiety in musicians. However, the effects of these techniques on music performance, respiratory function and posture remain inconclusive.

Musician Response to Injury

Rickert et al. (2014)[22] mention the existence of an orchestral culture in which musicians may see injury as a sign of weakness or poor musicianship. This tends to prompt continued performance despite pain. Worried over potential judgment, musicians have been found to conceal injuries from colleagues and management staff.

Dommerholt (2010)[23] notes that when injured, many musicians seek advice from posture or movement specialists before consulting with a traditional healthcare provider (physician or physical therapist). A common approach of injured flautists was to take Alexander lessons rather than pursue professional health advice (Ackermann et al., 2011)[24].

Ioannou and Altenmuller (2015)[25] reported that up to 35% of affected instrumental students did not seek help at all. Those who did seek help elected to request advice first from their instructor, and secondly from a physician. Those who consulted with physicians regarded subsequent medical treatments as only partially helpful for PRMDs.

SEARCH STRATEGY

The purpose of this scoping review was to assess the available literature body that examines the role of posture and balance stressors as risk factors in pain for players of hand-held musical instruments. The effect of posture on instrumental biomechanics and PRMDs may cross disciplines; potential literature may reside in performance, pedagogical, kinesiology and medical/occupational health study areas. It is doubtful that any single database will adequately capture the breadth of available literature. One goal of the present study was to determine which databases would be most likely to have information on posture and balance in musicians with musculoskeletal pain. After consultation with academic library staff and experienced health, music and kinesiology instructors, the search was conducted in the databases Medline, Web of Science and SportDiscus.

Methodology guidelines from PRISMA-ScR [26] and Peters et al. [27] were followed in process development. The search and filtering process for the study is outlined in Table 1.

Table 1

Steps in present study

Stage	Process
1 – Database search	Search of Medline (Ovid), Web of Science, SportDiscus
2 – Title review	Title confirmation that article is study of musicians with pain or posture/balance - for inclusion in Endnote database
3 – Abstract review	Abstract review via database to select only studies discussing **both** balance/posture, **and** pain – for inclusion in full-text review
4 – Full text review	Full-text review assessing relationship between pain and posture/postural awareness/balance

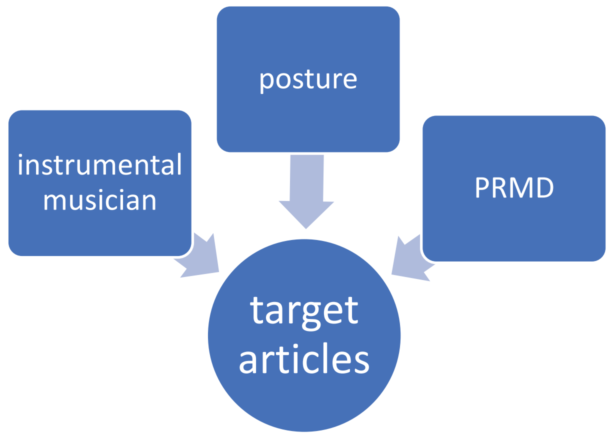

Figure 1: Conceptual search parameters. PRMD = playing-related musculoskeletal disorders

For the present search, there were three grouping areas of search parameters, with slight adjustments to suit the functionality of each database. The Medline (Ovid) search terms were: [posture.mp or exp POSTURE/ OR postural balance.mp or Postural Balance/ OR exp Muscle Tonus/ OR postural quality.mp OR Alexander technique.mp OR exp Mind-Body Therapies/ or Feldenkrais.mp OR exercise therapy.mp or exp Exercise Therapy/] AND
[exp Musculoskeletal Diseases/ OR exp Back Pain/ or musculoskeletal pain.mp or exp Pain/ or exp Musculoskeletal Pain/ or exp Neck Pain/ OR exp Occupational Diseases/] AND
[exp MUSIC/ OR musician*.mp].

The SPORTDiscus/Web of Science search terms were: [music* OR trumpet OR trombone] AND [alexander OR alexander technique OR balanc* OR body OR body learning OR equilibrium OR Feldenkrais OR learning OR mapping OR musculoskeletal OR musculoskeletal equilibrium OR postur* OR postural balance OR technique] AND [occupational diseases OR pain OR pain*].

For the title and abstract review phases, inclusion criteria for study retention was limited to language indicating that the study involved instrumental musicians and commented regarding balance/posture and pain. This was conducted by the lead author, with subsequent review by the co-authors. Studies retained for full-text review were not filtered further, all undergoing read-through by the lead author, then subsequent review and confirmation by the co-authors. The results of this phase were "mapped" in tabular form, the columns classifying conceptual categories

In keeping with scoping review intent, the full-text review assessed the availability of current literature for commentary regarding the existence of a relationship between posture/balance and pain in instrumental musicians. The quality of the research findings from each study was not an intended outcome. Accordingly, the template for the full-text review phase prompted study assessment for publication type, study design, focus, methodology, statistical methods, and results/conclusions. A final comment on each study was prompted regarding the existence of clear narrative indicating a relationship between posture and PRMDs.

RESULTS OF SEARCH

The Medline (Ovid) search produced 149 articles, 58 of which appeared relevant from title review, with SPORTDiscus identifying 75 articles, 12 of which were relevant based on title. Web of Science produced 1,179 articles, with 170 deemed relevant (see Table 2). Relevant references from each database were uploaded to EndNote X7 bibliographic software.

Table 2

Database search output (combined dates)

Database/date of search	Articles identified	Number relevant (by title)	Relevant and exclusive to this database (%)	Relevant and originating from MPPA journal
Ovid Medline Oct 12, 2018 and Oct 20, 2021	149	58	48 (82.8)	21
Web of Science Oct 8, 2018 and Oct 23, 2021	1,179	170	161 (94.7)	70
SportDiscus Oct 7, 2018 and Oct 23, 2021	75	12	5 (41.7)	0
Total	1,403	240		77

For both Medline (Ovid) and Web of Science, over 82% of the relevant articles were identified exclusively by each database, suggesting that different databases do access different sources, with no single database providing adequate capture. Of the 1,403 articles identified, 240 were judged relevant on the basis of title (see Table 3). Title review parameters included mention of instrumental musicians, plus some component of musculoskeletal (MSK) pain, medical issue, posture, balance, or body awareness modality. Articles devoted specifically to embouchure, hand or dystonia problems were not included.

Further filtering of articles to retain for full text review was based on combined abstract and title assessment, retaining only those reporting on musicians playing hand-held orchestral instruments, plus offering comment on both posture and playing-related pain. Mention of body awareness modality such as Alexander Technique was deemed an appropriate surrogate for posture mention.

Table 3

Search process article numbers to full text review

Initial articles identified	Relevant by title	Retained after abstract review	Full text review conducted	Comments on posture and PRMD relationship	Interventional study	Observational study	Review/ descriptive
1,403	240	31	29	15	10	11	8

The database search was conducted, using identical search terms and strategy, in October 2018, and again in October 2021, with results combined; otherwise, there were no overall date filters applied. The articles retained to full text review required English text (or translation) and library (including inter-library loan) availability, and spanned publication years from 2004 to 2020 (see Table 4). A summary of the search process and outcome is in Figure 2. A detailed list of the articles chosen for full text review, and summary of each, is in Table 5.

Table 4

Publication years

Year	2004	2007	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020
Article numbers	1	1	3	2	1	4	3	2	3	5	1	3

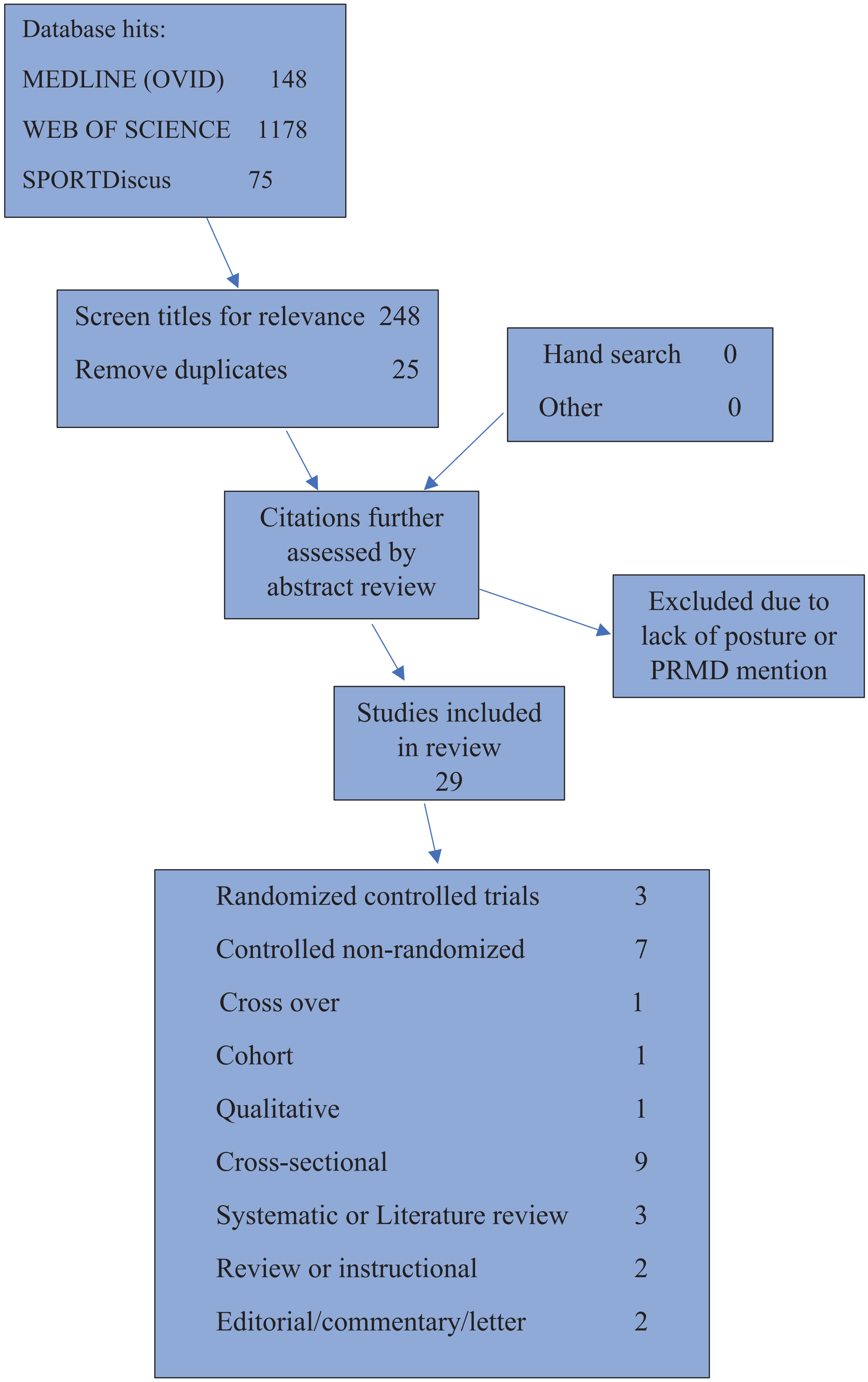

Figure 2: Search process and summary of source characteristics

Table 5

Full-text article review summary

AR=some comment on relationship of posture and PRMD; NAR=no comment re relationship

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
Fjellman-Wiklund et al. (2004)[28]	Journal article	Focus: Intervention Design: Non-randomized, interventional trial	5 professional violinists (intervention); 14 teacher/student (controls)	Intervention: body awareness technique Outcome measures: Quantitative: EMG analyses of trapezii before and after 8-week training in Basic Body Awareness Therapy (Basic BAT) Qualitative: participants interviewed re perception of changes in breathing, tension	Non-parametric testing to compare groups; SPSS and Matlab	no differences in EMG-demonstrated muscle activity between a group of violinists practicing a body awareness technique and a non-training group, but Basic BAT-trained group perceived improvements in breathing, muscular tension, postural control and concentration during practice sessions.	NAR Suspect potential for greater impact in **less** experienced players Limitations: small sample sizes; non-random assignment to intervention groups
Nyman et al. (2007)[29]	Journal article	Focus: Prevalence Design: Cross-sectional study	4 participant groups, 235 professional orchestra players, designate by arm position and playing time duration	Intervention: N/A Outcome measures: Questionnaire re instrument played and pain level in three anatomic areas. Arm position not measured but assigned on basis of instrument played; playing time not measured but assigned on basis of instrument played, type of ensemble, and repertoire style.	Odds ratios established by logistic regression using SPSS	Musicians working in an elevated arm position (e.g., violinists, violists, flutists, and trumpet players) had a higher prevalence of neck-shoulder pain than those working in a more neutral position. Control for number of potential confounders; recognition of different daily playing times for different instruments **and** repertoire types	AR Limitations: design does not allow determination of impact of differential arm position between individuals **within** an instrument group
Chen (2010)[30]	Book chapter	Focus: Prevalence Design: Cross-sectional study	300+ music major students in Taiwan – orchestral and keyboard instruments	Intervention: N/A Outcomes: Questionnaire data	Logistic regression data in tables, little explanation or detail	Assesses prevalence; finger symptoms exhibit U-shape relationship between rates and instrumental experience level suggesting experience beneficial to a point in time and thereafter disadvantageous. For arm, back, neck and wrist (areas the authors indicate simply maintain posture), disorder rates increased with	AR Limitations: comment on posture/prevalence vs time makes assumptions re causality; little evidence re areas claimed to simply

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
						experience level. Authors claim performance posture for these areas is fixed during the initial learning period, subsequently difficult to change.	maintain posture (static vs dynamic)
Dommerholt (2010)[23]	Journal article	Focus: Instructional review Design brief case studies as examples	Orchestral and keyboard instrumentalists	Selected examples from literature	NA	Healthcare providers need familiarity with demands of each instrument, impact on posture, range of motion, injury patterns, ergonomic demands. Musicians should be examined while playing their instruments. Musicians can educate care providers on aspects of the instrument, repertoire, and playing techniques.	NAR Instructional, informative Limitations: unclear re evidence-base in cases
Steinmetz et al. (2010)[17]	Journal article	Focus: Prevalence Design: Retrospective (26) and prospective (58) cohort study	84 Musicians presenting to specialized clinic with PRMD	Intervention: N/A Outcomes: descriptive data from clinical exam by First author (physiatrist) on all participants	Descriptive statistics, cross tables and $\chi 2$ tests, via SPSS	93% of participants showed dysfunctions in one or more postural stabilization system (85% scapular stabilization system, 71% lumbopelvic stabilization system, 57% upper crossed syndrome). Differences in lumbar stabilizer dysfunction noted between instrument groups. Scapular stabilizer problems and upper crossed syndrome more frequent in women.	AR Limitations: high risk for selection and observer bias; no control group
Lee (2012)[31]	Journal article	Focus: Interventional Design: cross-over, randomization to different intervention sequences	15 college instrumental musicians	Intervention: Each of two groups exposed to two interventions, in opposite order. Nil other control group. Included breathing exercises and physical therapy exercises. Outcomes: Sampling before and after total interventions (no mid-point), via (previously) validated self-report surveys: Health-Pain-Injury Inventory (HPI) and the	Small sample sizes, n=4 for the post-intervention evaluation	College musicians were not well aware of posture, tension, and movement flexibility. No differences between self-reported pre and post assessments in pain and injury. Combined breathing and strengthening/flexibility exercise program showed increased physical efficacy (awareness and comfort of posture and awareness of tension).	NAR Limitations: Insufficient numbers for post-intervention sampling. No mid-point sampling, little comparison between the two interventions

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
				Physical & Musical-Performance Efficacy Assessment Survey (PME)			
Park et al. (2012)[32]	Journal - Comparative study	Focus: Prevalence Design: Cross-sectional study	9 violin students with neck pain; 9 violin students without neck pain (control)	Intervention: NA Outcomes: EMG data and 3-dimensional ultrasonic motion analysis system assess active neck ROM (non-playing) and EMG activity/neck motion (while playing)	Independent t-test via SPSS	Left lateral bending/rotation greater in neck pain group. EMG activity of the left upper trapezius, cervical extensors, and sternocleidomastoid muscles greater in neck pain group. Active ROM of left axial rotation was significantly lower in the neck pain group. Results suggest that an asymmetric playing posture with increased muscle activity and decreased neck axial rotation may contribute to neck pain in violin students	AR Limitations: weak evidence of causality, does not demonstrate predictor to precede outcome
Lee et al. (2013)[33]	Journal - Review article	Focus: Descriptive Design: Review article	String players	Intervention: NA Outcomes: General description of instrument demands and postures, typical MSK complaints	NA	Descriptive and instructional	NAR Descriptive only
Arnason et al. (2014)[34]	Journal article	Focus: Prevalence Design: Cross-sectional	74 music students divided into 2 groups based on school-type of origin (classical vs rhythmic music school)	Intervention: NA Outcomes: Questionnaire re cumulative and current prevalence, and severity, of PRMD	Chi square and independent t-tests, via SAS Enterprise and Microsoft Excel	A higher prevalence of PRMD in classical schools compared to the rhythmic music school. Authors conclude this as due to different demands of the instruments and composition on playing posture.	AR Assumes posture difference between the music types Limitations: nil evidence presented supporting assumption; weak evidence re causality
Baadjou et al. (2014)[4]	Journal article	Focus: Interventional Design: single-blinded, group	150 music school students	Intervention: intervention group (n = 75) receive biopsychosocial prevention program including postural training via Mensendieck or Cesar method	Multilevel mixed-effect logistic or linear regression analyses	Protocol/proposal – no results	AR See Baadjou, 2018 Offers potential for good quality evidence in an interventional trial

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
		randomized controlled trial (protocol proposal)		Total follow-up duration is two years. Outcome: primary outcome measure is disability (Disabilities of Arm, Shoulder and Hand questionnaire). The secondary outcome measures are pain, quality of life and changes in health behavior.			
Chan et al. (2014)[35]	Journal article	Focus: Interventional Design: Non-randomized interventional trial	85 professional orchestra musicians volunteered to Intervention or control group	Intervention: intervention group (n=60) receives 10-week exercise intervention Outcomes: pre, post and 6-month follow-up questionnaire re PRMD frequency and severity	SAS statistical software 9.0, basic descriptive statistics, plus univariate and then multivariate linear regression.	Exercise group had a higher baseline PRMD frequency and severity compared to the control group; exercise group showed a significant reduction in the frequency ($p<0.05$) and severity ($p<0.05$) of PRMDs at T1 compared to controls; reduction maintained at T2, but not statistically different from control group.	NAR Limitations: self-selection process creates bias; different **baseline** levels of outcome variable complicates interpretation
Manchester (2014)[36]	Journal - editorial	Focus: Descriptive Design: Editors review and commentary	NA	Intervention: NA Outcomes: Comparison of occupational health investigation standards re quality of evidence to performing arts medicine articles commenting on role of posture.	NA	From occupational health literature: 1. convincing evidence exists for a posture role in neck, shoulder, wrist, hand, and low back injuries 2. Highest quality of evidence would require: (1) high participation rate (data on over 70% of eligible subjects); (2) use of both symptoms and physical findings determining condition; (3) investigators blinded to exposure status and investigated outcome; (4) direct observation of risk factor preferred over self-report.	AR Commentary

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
Ioannou et al. (2015)[25]	Journal article	Focus: Prevalence Design: Epidemiological cross-sectional study	180 instrumental music students	Intervention: NA Outcomes: Paper questionnaire – seeking detail on presence of any PRMDs, number of hours of practice, treatment, student perceptions re cause of PRMD	Combination of multiple parametric and nonparametric tests, plus Pearson's and Spearman's correlation. Via SPSS analysis	PRMDs have origin as early as secondary and university levels. Increased hours of practicing is a risk factor. Students' reports indicate strong belief that abnormal body posture has a crucial role in problem development. Students tend to seek help from their instrumental tutors, with medical doctors the second option. Comments indicate desire for more specialized doctors in musicians' medicine and note the importance of close collaboration between physicians, instrumental tutors, and students.	NAR Authors note validated standardized questionnaires for future evaluations may be preferable. Limitations: self-reports and questionnaires may lack reliability; no professional posture evaluation
Steinmetz (2015)[37]	Journal article	Focus: Descriptive Design: Literature review	Review studies on instrumental musicians	Intervention: NA Outcomes: Descriptive, comparative	NA	Published studies associate playing musical instrument with postural disorders; music students show twofold higher risk of musculoskeletal problems compared to non-music students. PRMD frequently associated with impairment of postural stabilization systems.	NAR Limitations: full text in German; only abstract available in English
Teixeira et al. (2015)[38]	Journal article	Focus: Prevalence Design: Cross-sectional study	Semi-professional violin and viola players	Intervention: NA Outcomes: Pain evaluation via Corlett and Bishop (1976) questionnaire; posture evaluation by assessment of video recordings of participants over eleven rehearsal sessions	Not available	Pain complaints in neck, upper back, shoulder and left arm; symptom association with posture extremes adopted during instrumental playing, particularly cervical flexion, left shoulder internal rotation and left shoulder elevation. Posture analysis suggests unnecessary muscle contraction and stressful positioning over the entire practice period with the instrument.	NAR Limitations: full text article not located (including via inter-library loan); abstract does not report number of participants
Blanco-Pineiro et al. (2016)[39]	Journal article	Focus: Descriptive	Review studies on	Intervention: NA Outcomes: 27 descriptive and 14 interventional English-language	SPSS	81.5% of the descriptive studies identified an association between postural quality and some other	AR Comprehensive review of existing

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
		Design: Literature review	instrumental musicians	studies, published between 1989 and 2015 describing the relationship between posture during performance and various musical quality and health factors. Studies characterized according to sample parameters, temporal design, posture and musculoskeletal health variable evaluation methodology, additional risk factors, and results/conclusions regarding relationships between posture, musculoskeletal health, and musical performance.		variable (physical or musical performance, PRMDs, or musical activity variables); 6 of the14 interventional studies found clear positive effects, 5 observed positive effects on some target variables but not others. Analysis of results was hampered by disparity of measuring instruments and variable definition. Empirical knowledge base has limitations, making comparative analysis difficult.	studies; could be described as a scoping review Limitations: meta-analysis not feasible
Woldendorp et al. (2016)[40]	Journal article	Focus: Prevalence Design: Cross sectional study	141 professional and student double bassists and bass guitarists	Intervention: NA Outcomes: Self-reported functioning, location and intensity of musculoskeletal complaints, collected online via self-constructed and existing questionnaires; analysis for associations between work-related postural stress (determined by type of instrument) and physical complains, adjusted for potential confounders.	Logistic regression analyses, SPSS	Logistic regression analyses revealed no association between complaints and the playing position of the left shoulder area in double bassists, right wrist area in the bass guitarists, or the right wrist area for German versus French bowing style. In this sample, long-lasting exposures to postural stress were not associated with musculoskeletal complaints, which does challenge a dominant model in pain medicine (to focus on ergonomic postures).	AR Limitations: assumes that the instrument type is an appropriate surrogate marker for posture quality
Kok et al. (2017)[41]	Journal article	Focus: Prevalence Design: Cross sectional study	162 amateur musicians subjects who indicated playing a musical instrument, without attending a music academy	Intervention: NA Outcomes: Web-based survey of amateur musicians, re prevalence of musculoskeletal complaints and playing time. Two researchers (TD and LMK) independently identified the arm position of the instrument groups, to assign arm posture	t-test, chi-square and Mann-Whitney U-test to compare outcomes. Logistic regression re playing time and arm	Left shoulder complaints were five times higher in elevated-arm instrument assignment compared to a neutral-arm instrument. Authors hypothesize this could be due to decreased blood flow to shoulder muscles with the arm elevated, or from higher biomechanical shoulder joint reaction force in this position, leading to higher muscle strain	AR Authors note low response rate of this study; self-reporting, no objective arm position measures Limitations: assumption that instrument type predicts arm

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					position as predictors of symptoms		elevation, without control for other instrument variables (weight, playing factors)
Shoebridge et al. (2017)[42]	Journal article	Focus: Descriptive Design: Qualitative study	Purposive sampling of seven individuals from professional groups often consulted by musicians about PRMP.	Intervention: NA Outcomes: Aim of study was to develop an interdisciplinary theory of posture. Framework of constructivist grounded theory (pragmatism based) for conduct of semi-structured interviews of leading music teachers, physiotherapists, and Alexander Technique teachers. Transcripts analyzed by grounded theory; results discussed applying Theory of Planned Behavior. Interview transcripts coded line-by-line, constant comparative analysis to test codes and inform emergent categories; early codes focused to achieve theoretical saturation.	Memos in the analytical process. A reflexive diary, and cross-disciplinary consultation involves all research team for data triangulation throughout.	Posture defined as a dynamic expression of biopsychosocial factors specific to time, place, person and context, supersedes the conventional biomechanical model of posture. Participants concurred that optimal posture for musicians should allow the best performance with the greatest efficiency, with function as the focus. Minding the Body conceptually includes five interrelated subprocesses: maintaining ease, finding balance, challenging habits, expanding the framework, and barriers to change.	NAR Broadens perspective re posture and meaning to the musician. Limitations: uncertain applicability in reducing PRMD prevalence
Taheri et al. (2017)[43]	Letter to editor	Focus: Descriptive Design: Referenced commentary	Violin players with neck pain	Intervention: N/A Outcomes: Authors note physio-psychological nature of violinists' neck pain, comment on literature and question if treatment could benefit from addition of therapies that address postural and movement habits.	NA	Alexander technique believed beneficial in postural stability, muscular harmonization, and relaxation for chronic pain. Some studies suggest that Alexander technique, as a single approach, is effective in reducing performance anxiety in musicians. The addition of Alexander technique to established therapies, and its effect on PRMDs among musicians with chronic neck pain, warrants further study.	AR Limitations: commentary without evidence

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
Arnason et al. (2018)[44]	Journal article	Focus: Interventional Design: Prospective descriptive comparative study	23 music students, divided into prevention group (PG, 13 students) and comparison group (CG, 10 students) based on enrollment or not, in a musician health course	Intervention: PG course was 4 lectures and 16 practical sessions via10 weekly sessions in each semester Outcomes: Before and after the course, participants answered a questionnaire re level of physical activity, warm-up exercises, health-promoting activities, and subjective body awareness during musical performance and activities of daily living (ADL).	IBM SPSS and Microsoft Excel; Chi-square and McNemar tests between groups and time points. ANOVA regarding subjective body awareness	PG group increased, and CG lessened, the amount of warm-up. Significant interactions for subjective body awareness scores (between groups over time) during practice and during ADLs, PG group with greater positive change over time. No group differences in students' subjective rating of body awareness during live performance. Benefit may be due to improved subjective body awareness and prevention focus.	NAR Limitations: differences between CG and PG group at onset suggest selection bias; small sample size; unclear if self-reports/subjective evaluation re body awareness are valid measure of true effect
Baadjou et al. (2018)[45]	Journal article	Focus: Interventional : Design: Randomized controlled trial with intention-to-treat analysis	170 conservatory students randomized to experimental (n=84) or control (n=86) groups	Intervention: Experimental group attends 11 classes on body posture (playing the instrument) and performance-related psychosocial aspects. Control group attends five classes promoting general physical activity according to national guidelines. Outcomes: Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire, with outcomes assessed at six points, from baseline until 2-year follow-up.	Independent samples t-test, Mann–Whitney U-test or chi square test. Group effects by logistic generalized estimating equations	Focus of first six classes was body posture while playing, incorporating therapy principles of Mensendieck or Cesar. Themes include body awareness, balanced posture and controlled movements; awareness of tension and relaxation; and functional respiration. No differences between groups for any outcome. A biopsychosocial prevention course not superior to physical activity promotion in reducing disability	AR This is the report for outcome of the 2014 Baadjou proposal for PRESTO study. Large sample size. Limitations: large proportion lost to follow up by study end
Schemman, Rensing, & Zalpour (2018)[46]	Journal article	Focus: Descriptive Design: Literature review	High string musicians (violin, viola)	Intervention: N/A Outcomes: Systematic literature search in databases Cochrane, CINAHL, and PubMed as well as the journal Medical Problems of Performing Artists. Sixty-four studies conducted between 1999 and May 2017 were included according to predefined inclusion criteria.	NA	Various biomechanical instrumented assessments, clinical examination techniques, and self-report instruments regarding musculoskeletal system identified and systematically categorized. Assessments could be used to further the understanding of contributing factors to PRMD in	NAR Detailed literature review and description of lab methodology for study of kinetics in string musicians

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
						high string players in further research and clinical work.	
Cervero et al. (2018)[47]	Journal article	Focus: Intervention-al trial Design: pre and post comparison; no control group or blinding	Professional clarinetists, chosen by convenience sampling	Intervention: Single group - 2-month instrument-specific exercise program Outcomes: Pre and Post intervention Langlade postural test AND self-report "faces" pain scale	SPSS t-test compares pre and post scores of pain and posture. Bivariate correlation of pain and Langlade	Moderate relationship (correlation value = 0.582) between shoulder girdle pain and Langlade	AR No control group or blinding – potential bias in pain self-reporting. Specific to a single instrument. Does suggest association between pain and posture
Ohlendorf et al. (2018)[48]	Journal Article	Focus: Interventional Design: Non-randomized, multiple intervention comparative	47 musicians, variety of instruments. 3 groups: professional, student, amateur	Intervention: All participants assessed using 6 ergonomically-differing chairs Outcomes: MiniRot-Kombi back scanner, assesses upper body posture and seating mat assesses pressure pattern	Factor analysis, then MANOVA and ANOVA	Chair cushion decreases mean pressure up to 30%. Additional force from holding the instrument exceeds actual instrument weight. No relationship between pressure and upper body posture. Intersubject variability is larger than differences introduced by chair or instrument	NAR No apparent attempt to demonstrate posture association with pain. Complex statistical analysis of varying playing conditions.
Shanoff et al. (2019)[49]	Journal Article	Focus: Prevalence Design: Cross sectional study	109 professional and college level saxophonists respond to survey request	Intervention: N/A Outcomes: Questionnaire data, addresses playing habits, pain prevalence/location, strap use, postural habits	Friedman, Wilcoxon across postures; Spearman's between posture and pain	Positive correlation between rounded upper back, backward pelvic tilt and pain	AR Correlation between specific postures and pain. Volunteer self- reporting creates potential bias. Self- report of posture, no objective assessment.

Study	Publication type	Focus/Design	Participants/ Population	Methodology	Statistics	Main results and conclusions	Reviewer comments
Davies, J. (2020)[50]	Journal article	Focus: Interventional Design: pre and post comparison; no control group or blinding	23 performance - degree students (18 undergrad, 5 postgrad). Variety of instruments	Intervention: Participant self-selection by volunteering. Single group 14-week Alexander Therapy (AT) teaching Outcomes: Pre and Post intervention questionnaire seeking numerical rating of degree of benefit from the AT instruction	Mean/SD reporting of change scores	Mean improvement scores: Posture = 2.60/3.00 Pain = 2.24/3.00 Total benefit = 2.10/3.00 (SD = 0.54)	NAR Improved pain and posture, but treated as independent outcomes. No control group or blinding. Subjective participant rating of both pain and posture
Davies,J. (2020)[51]	Journal Article	Focus: Interventional Design: pre and post comparison; no control group or blinding	14 performance -degree students; variety of instruments. Raters included 8 instructors	Intervention: Separately reported extension of Davies 2020 (above), 14-week AT teaching Outcomes: participants and instructors, review pre and post audio-visual recordings - rated for degree of improvement in tension, posture, movement	Mean/SD reporting of change scores. Mann-Whitney compares student and instructor ratings	Mean posture rating improvement score = 2.75/5.00 post AT intervention. Minimal difference between student and instructor ratings of improvement	NAR Intended to add objective rating of posture improvement; unclear criteria for video scoring. No control group or blinding. Unclear association between posture/pain.
Poncela-Skupien et al. (2020)[52]	Journal Article	Focus: Interventional Design: Randomized control trial, intention-to-treat analysis. Evaluator blinding for posture assessment	25 string students, aged 10-14, recruit via convenience sampling	Intervention:4 weekly exercise sessions; control group = therapeutic exercise only, intervention group = therapeutic exercise + Pilates Outcomes: At 0 and 4 weeks: subjects report pain scores with VAS; blinded therapist assessor rates postural alignment of shoulders and hips utilizing Kinovea video analysis software	SPSS non-parametric, multiple tests including Fisher's exact test, Mann-Whitney U test, Wilcoxon signed-rank	Experimental group demonstrated decreased pain in before and after playing setting; control group showed decreased pain in before playing setting only. No improvement either group in pain **during** playing. No change in shoulder or hip alignment for either control or experimental groups	AR Improved pain status in group that included Pilates prompt authors to credit postural effect of Pilates. No measured alignment changes however.

DISCUSSION

Overall, studies located by the literature search were observational (11 of 29), interventional (10 of 29), or review/descriptive (8 of 29). Most observational studies were epidemiological, typically cross-sectional and reporting on PRMD prevalence without evidence-based analysis. In later years there was a trend toward more interventional studies, pre-October 2018 these were only 5 of 23 (22%), with the three-year timespan post-October 2018 finding 5 of 6 (83%) studies of this orientation.

Ovid Medline and Web of Science were effective in locating relevant citations of literature regarding musicians with pain. Approximately half of the citations were studies published in Medical Problems of Performing Artists. Of the 29 manuscripts which met criteria for full text review, eight were published between 2004 and 2013, while twenty-one were published between 2014 and 2020, suggesting increasing research interest in the area of musicians and musculoskeletal pain. Two of the studies meeting title and abstract criteria did not undergo full text review, due to lack of English full text version availability via interlibrary loan.

Search results suggest a larger body of literature regarding injuries in string musicians, with a smaller number of studies for brass and woodwind instruments. Fifteen of the twenty-nine full-text articles offer some comment regarding a relationship between posture and PRMD. For most, the language suggested that the importance of posture and balance in the development of pain symptoms was assumed, rather than proven.

The effectiveness of postural awareness/therapeutic movement techniques popular with musicians, including body mapping, Alexander Technique [25], Feldenkrais [53], and Mensendieck [54], remains unclear. Though the Schemmann et al. (2018)[46] systematic review covers technology options available for posture assessment, only three pre-October 2018 studies in the full-text review utilized such technology. These included Park et al. (2012)[32] via EMG and ultrasonic motion analysis, Fjellman-Wiklund et al. (2004)[28] via EMG alone, and Teixeira et al. (2015)[38] via video review. Three of the six post-October 2018 studies involved some objective posture assessment, suggestive of a potential trend away from simple subjective reporting. This included Cervero et al. (2018)[47] via Langlade posture test, Ohlendorf et al. (2018)[48] with MiniRot-Kombi back scanner, and Davies,J. (2020)[51] via video review.

There were some limitations to this scoping review. The search was limited to three databases. It remains possible that manual or less formal literature review methods, including attempts to access unpublished reports and data, might have contributed to a broader picture. This scoping review stopped in 2020. Thus, there were no studies included for 2021.

The studies that were included in this scoping review offered little to confirm that body or upper extremity motion per se were primary risk factors for PRMD. Motions of trunk and arm create repetitive balance/posture deviations which require compensation and activation of muscles to stabilize the body for performance. Only a few studies made conceptual distinctions between dynamic and static factors influencing both motion and posture control.

CONCLUSION

Musculoskeletal injuries can have a negative impact on music performance opportunites and professional careers. Focal overuse trauma has been studied for a variety of occupational areas, with extrapolation of evidence regarding pathophysiological principles to focal overuse injuries in musicians. However, there is minimal specific knowledge regarding the influence of complex mechanisms involving posture and balance and their impact on overuse injuries in musicians. The contribution of posture and balance deviations to musculoskeletal injuries in muscians have little cited evidence in the studies identified by this scoping review. An extension of epidemiological and biomechanical research could focus on evidence-based analysis of postural righting mechanisms and the functional influence of posture and balance on neuromusculoskeletal injuries in musicians. Validation and standardization of posture and balance assessment is a necessary component for research directed at establishing a relationship between postural righting challenges and symptomatology. The effectiveness of preventive strategies, including movement awareness strategies and techniques also warrants further rigorous research inquiry.

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CHAPTER 3: paper prepared for submission to ITA (International Trombone Association) journal

Motion Capture Technology and Ground Reaction Force Measurement in the Study of Biomechanics of Playing the Trombone

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CHAPTER 3: MOTION CAPTURE TECHNOLOGY AND GROUND REACTION FORCE MEASUREMENT IN THE STUDY OF BIOMECHANICS OF PLAYING THE TROMBONE

BRIEF DESCRIPTION

This is a proof-of-concept study for the utility and role of Vicon motion capture technology, Nexus software, and ground reaction force (GRF) measurement, in the evaluation of biomechanical factors for playing the trombone. The objective was to establish methodology able to simultaneously generate data regarding balance and multi-segment body positioning, in various slide positions. The underlying motivation was to better understand biomechanical factors contributing to left upper extremity (LUE) pain in trombonists.

BACKGROUND

There is a paucity of scientific and pedagogical literature regarding biomechanics, and optimization of posture, balance and musculoskeletal function, in playing the trombone. Review of instructional books, and dialogue with low brass instructors, indicates that only a few published guides discuss posture considerations, mostly in superficial manner and without cited evidence. A better understanding of biomechanical factors, particularly the weight-bearing and torque forces on the left hand and wrist relative to properties of the trombone and the shifting centre of gravity, may help outline determinants leading to playing-related pain. Benefits could include effective prevention strategy for teachers, and better treatment strategy for health care providers.

Wallace (2016) noted a hypothetical relationship between musculoskeletal problems and the biomechanical demands of the trombone. An orchestral tenor trombone weighs approximately 1.9 kg (Price, 2018), the left hand and flexor/pronator muscles of the forearm involved in bearing that weight, while also creating a compressive force against the embouchure. Such forces can range from 375 to 2,750 g for symphonic trombone players, often higher in students. The right upper extremity supports minimal weight, but provides motion of approximately two feet from slide positions one through seven, accomplished by motion involving fingers, wrist, elbow, shoulder and scapulothoracic joints.

The LUE is assumed to face primarily static loading, with the right facing dynamic loading. Neither extremity is subject to high-impact or high-load in playing, but the right sided dynamic load and left sided static load could contribute to overuse injury, via low-impact repetitive microtraumas. Visentin (2004) notes that repetitive use injuries typically involve loads well below physiologic limits, with either repetitive motion or sustained contraction producing microtrauma, the effects accumulating over time, rather than acutely. Static loads occur when muscle lengths remain near constant, and are thought to have higher potential for muscle injuries than dynamic loads, in which there is variability of muscle length.

Chesky (2002) noted that 60% of brass musicians report some playing-related musculoskeletal pain, trombonists with the highest rate at 70%. Problems of the left arm (shoulder, forearm, elbow, and wrist) are twice as commonly reported as those on the right side. An EMG (electromyography) study by Price (2018) noted that anterior deltoid, pectoralis and biceps EMG activity levels were all measured as higher for the left arm in trombone players.

Many authors refer to overuse syndrome in musicians as “performance-related musculoskeletal disorders” (PRMD). Ackermann (2012, p.182) defined performance-related musculoskeletal disorders as “any pain, weakness, numbness, tingling, or other physical symptoms that interfere with your ability to play your instrument at the level to which you are accustomed.”

One strategy that could inform the prevention and treatment of PRMDs in trombonists is the production of a quantitative kinematic description of the motions involved in playing. Motion analysis is fundamental in this process. There are no known currently-existing detailed motion analysis studies of trombone. The objective here was therefore to establish and evaluate a methodology able to simultaneously generate data regarding balance and multi-segment body positioning, in various slide positions.

METHODOLOGY

Model development

A study by Shan (2003) provides a methodological template for obtaining quantitative three-dimensional (3D) kinematic data on shoulders, elbows and wrists in violinists. As with trombone, the violin presents postural and load asymmetry, with static load challenges for the LUE while the right upper extremity (bow arm) faces dynamic load. Shan (2008) further described the combination of Vicon 3D motion capture and Nexus 1.7.1 software, with balance platform use, for the study of human subjects swinging a golf club. These studies provided an initial planning template for application of combined motion-capture and ground-reaction force technology to trombone.

For the present study, three areas were identified for evaluation. To assess dynamic weight transfer and balance forces of the standing human subject while playing, two Kistler force platforms (one for each foot) were utilized. Each platform measured force vectors in three planes, labelled as ground reaction force (GRF). Existing technique was sufficient, after axis alignment and calibration. Data recording was accomplished via an additional channel in the Vicon system. Secondly, the capacity to record the position of the instrument slide, and thirdly, the movement of multiple musculoskeletal segments of the human subject, each required a model recognizable by the Vicon technology. This involved construction of separate electronic models for the instrument and subject, both models then activated for data recording during the trial.

In the Vicon technology, each human subject has different anthropometric measures, requiring separate calibration to allow technology recognition of subject and segments. With existing standardized models of marker placements, a new design for the human subject was not required. Models involve a total of 39 reflective markers: 4 head (right and left frontotemporal and parietal); 9 trunk (1 sternal, 1 xiphoid, 1 at C7, 1 at T10, 1 to designate right back, 4 pelvic); 7 on each upper extremity (1 acromion, 1 upper arm, 1 lateral epicondyle, 1 lower arm, 1 ulnar styloid, 1 radial styloid, 1 at third MCP joint); 6 on each lower extremity (1 fibula head, 1 lateral malleolus, 1 hallux, 1 posterior heel, 1 upper leg, 1 lower leg).

An existing Vicon model for the instrument however did not previously exist. After trials seeking optimal reflective marker number placement, it was determined that adequate data collection and visual representation of instrument orientation and slide position, could be achieved with a configuration of six reflective markers on the instrument – three on the stationary (bell) section (tuning slide, upper edge of bell, upper leadpipe) and three on the mobile (slide) section, demonstrating motion and position of the slide.

Camera placement

For 3D motion capture, the Vicon system utilized ten cameras, each of which produced infrared light, then recorded reflections created by infrared reflector markers. Data was collected at 200 frames/second, allowing for a triangulated and time-stamped position recording for each marker. This resulted in a three-dimensional visual representation of subject and instrument via computer display. Trials determined optimum camera positioning for clear marker recognition and minimum infrared ghosting, related to reflections from surfaces other than intentional markers. The resulting camera configuration was for three cameras posterior to the subject, with seven anterior (ranging from left antero-lateral to right antero-lateral) (figure 3). The anterior cameras had diversity in height to better capture the entire subject and instrument.

Figure 4 demonstrates subject and instrument, with instrument in resting position at the subject's side, with Figure 5 showing playing position.

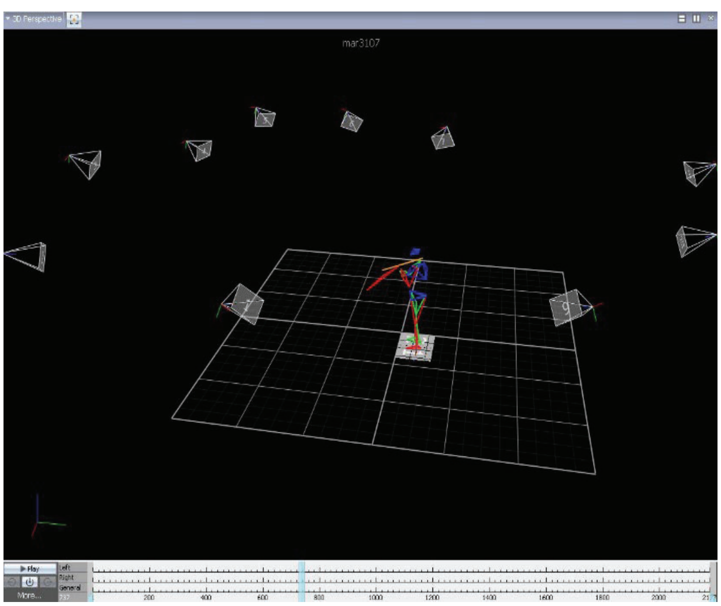

Figure 3: camera placement around subject, instrument and force platforms

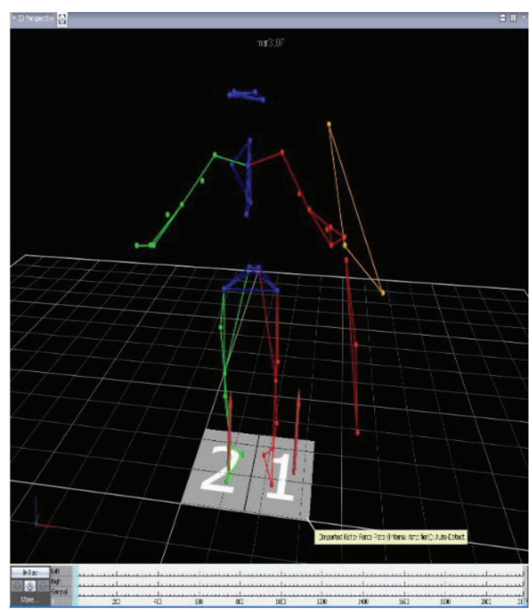

Figure 4: subject, with instrument at side

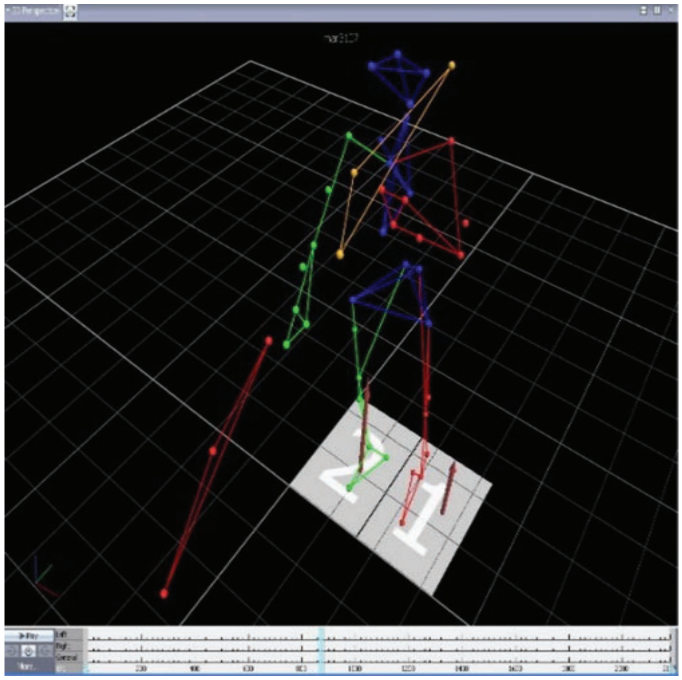

Figure 5: subject and instrument, while playing

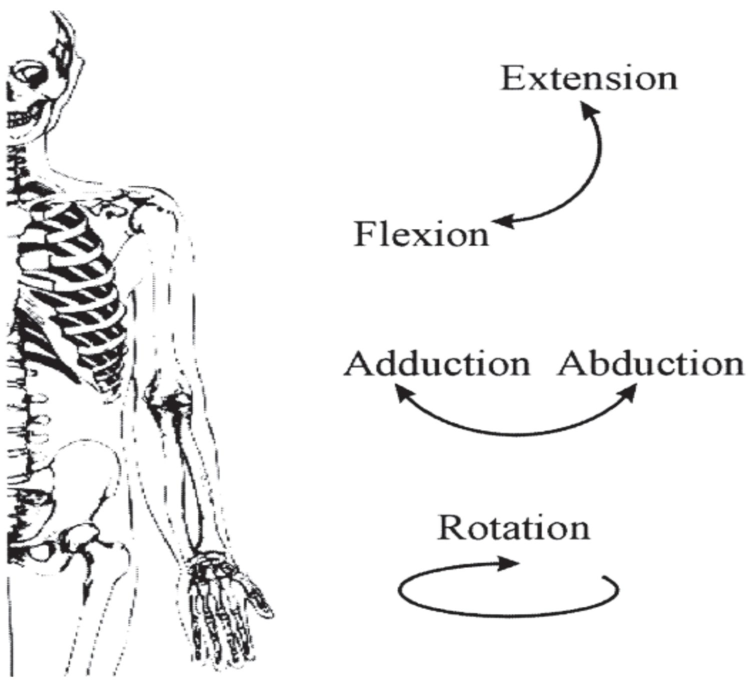

Figure 6: zero positions of upper arm joints (standard anatomical position). Flexion, abduction and pronation (thumb toward trunk) generate position angles; extension, adduction and supination generative negative angles. From Shan & Visentin (2003)

Recording

In trial data acquisition, a Vicon capture of the author raising and playing the instrument with a representative sampling of slide motion over an approximately 11 second period, was obtained and studied. Over the session, there were some marker label errors – these were manually corrected and re-labelled, with repair of a few missing body segments, in accordance with currently accepted Vicon Nexus protocol. When the video indicated completed segment data without gaps or errors, the resulting raw data was uploaded to an Excel file for further processing and evaluation.

Data provided the position of each marker, as well as shoulder, elbow, and wrist joint angles: flexion/extension, abduction/adduction, and rotation. All angles were in reference to standard anatomical zero position (Figure 4).

RESULTS

Effectiveness and utility of the technology and model design for collecting and recording the desired data was confirmed. Range of motion (ROM) data included three planes for shoulders and wrists (flexion/extension, abduction/adduction, rotation), and one plane for elbows (flexion/extension). GRF data in three axes was also reported, from one force platform under each foot.

Table 6 outlines the range of motion for shoulders, elbows and wrists during the portion of the study after the instrument was raised to playing position (achieved at frame 420). The range numbers indicate actual position range in degrees relative to the zero-reference position, while the number in parentheses indicates the total excursion amount for the specified plane of motion, in degrees.

For shoulders and wrists, joint motion in three axes is reported. The elbow functions mainly as a hinge joint, so only one axis is reportable, flexion-extension. The largest excursion was in right wrist rotation at 133 degrees (compared to left wrist rotation at 31 degrees). Relatively high flexion-extension and abduction-adduction for the right wrist is indicative of the complex multiple axes motion of the right wrist in extending the slide from first to sixth position.

The smallest excursion was noted for left elbow flexion-extension at 4 degrees, and left shoulder abduction-adduction at 10 degrees. Left wrist excursion in the playing position was also small with flexion-extension at 16 degrees total and abduction-adduction at 14 degrees.

Table 6

Range of motion of upper extremity joints (degrees) in playing position and during slide motion. Parentheses value indicates total

Joint	Side	Flexion-extension	Abduction-adduction	Rotation
Shoulder	Left	-1 to 26 (27)	14 to 24 (10)	23 to 53 (30)
	Right	16 to 45 (29)	8 to 24 (16)	22 to 53 (31)
Elbow	Left	120 to 124 (4)	NA	NA
	Right	28 to 114 (86)	NA	NA
Wrist	Left	5 to 21 (16)	20 to 34 (14)	79 to 110 (31)
	Right	-43 to 63 (106)	13 to 60 (47)	36 to 169 (133)

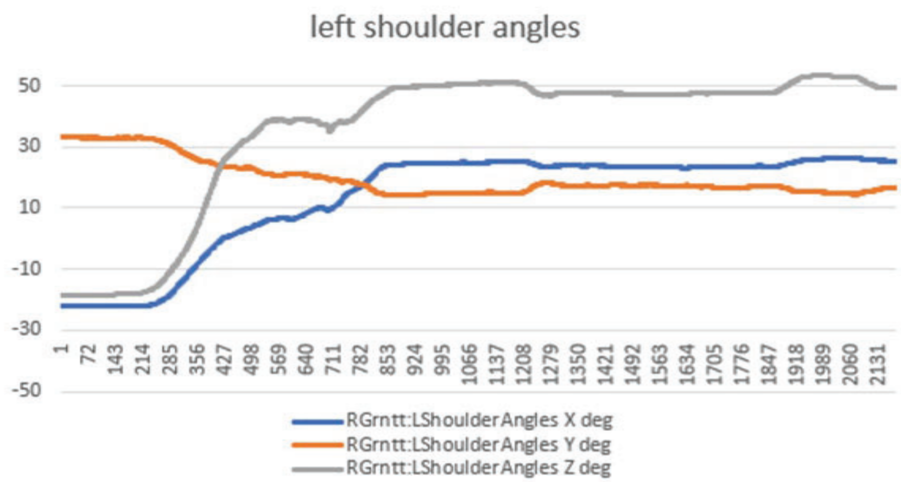

Figure 7: left shoulder angles during trial (degrees). Horizontal=frame, 200/sec

During the playing phase of the trial, shoulder angles on the left side are near-static, while right shoulder motion shows flexion, adduction and external rotation corresponding to the timing and degree of slide extension. Shoulder ROM data suggests primarily dynamic loading for right shoulder, and static loading for the left.

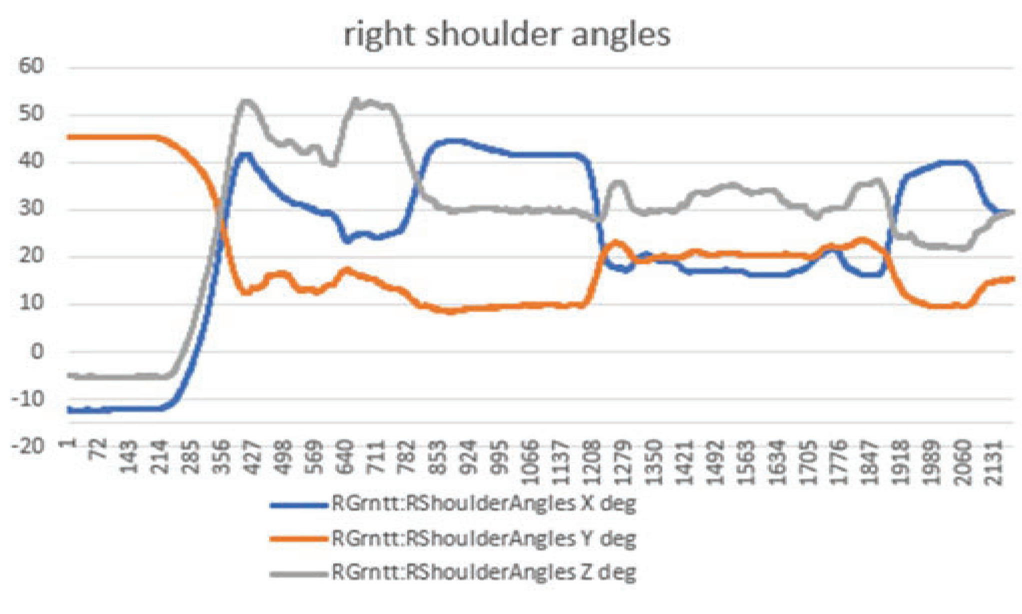

Figure 8: right shoulder angles during trial (degrees). Horizontal=frame, 200/sec

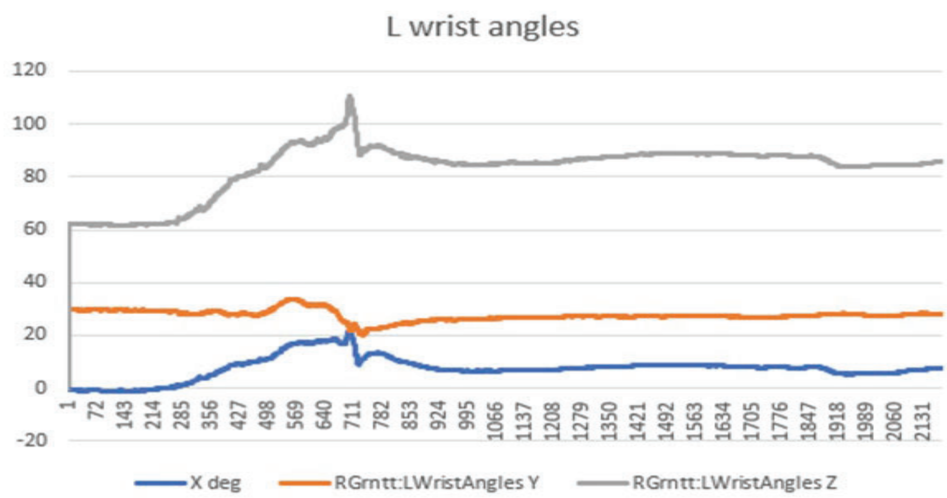

Figure 9: left wrist angles during trial (degrees). Horizontal=frame, 200/sec

Patterns for wrist motion are more complex to interpret. The left wrist, bearing most of the instrument weight, demonstrates minimal position change in the intial 420 frames while the instrument is being raised, an effort accomplished by the left arm alone. It remains mostly static thereafter, during slide motion.

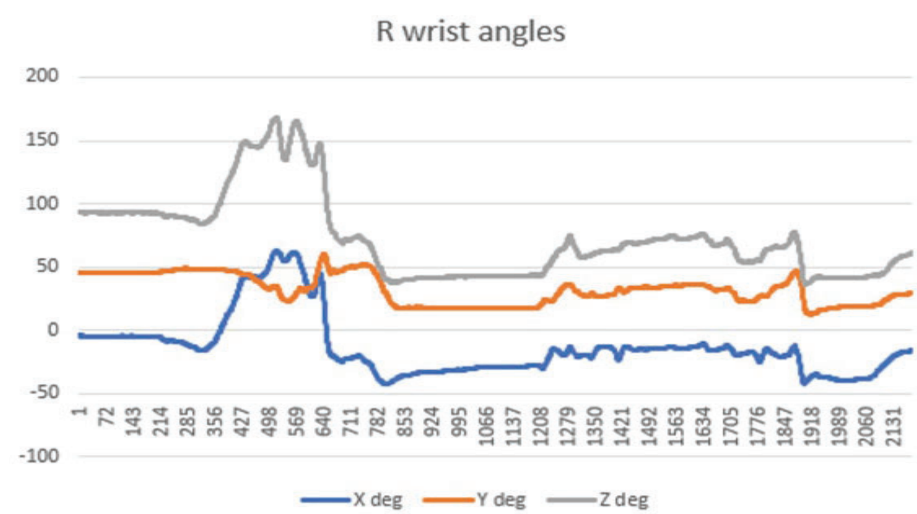

Figure 10: right wrist angles during trial (degrees). Horizontal=frame, 200/sec

The right wrist shows a flurry of activity over frames 400 – 700, mostly **after** instrument raise, and **prior** to slide extension. It is assumed that this period of activity relates to right hand action in releasing the slide lock. For the following period of slide motion, the right wrist, while demonstating some motion in all three planes, remains relatively static.

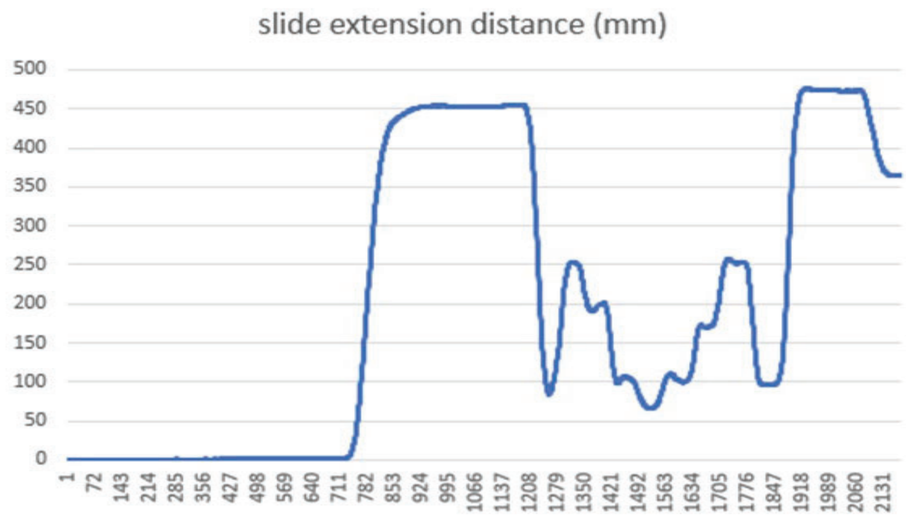

Figure 11: slide extension during trial (mm). Horizontal=frame, 200/sec

Slide extension begins at approximately frame 720, after the instrument has been brought up to playing position at approximately frame 420. Slide motion proceeds from position 1 to position 6, then between positions 2 and 4, this repeated, then back to position 6. It serves as reference for the other figures regarding timing of slide motion.

GRF over the trial suggests significant balance shifts both in reaction to the raising of the instrument (frames 1 to 420), preparation for playing (frames 421 to 720), and slide motion (frame 721 to conclusion).

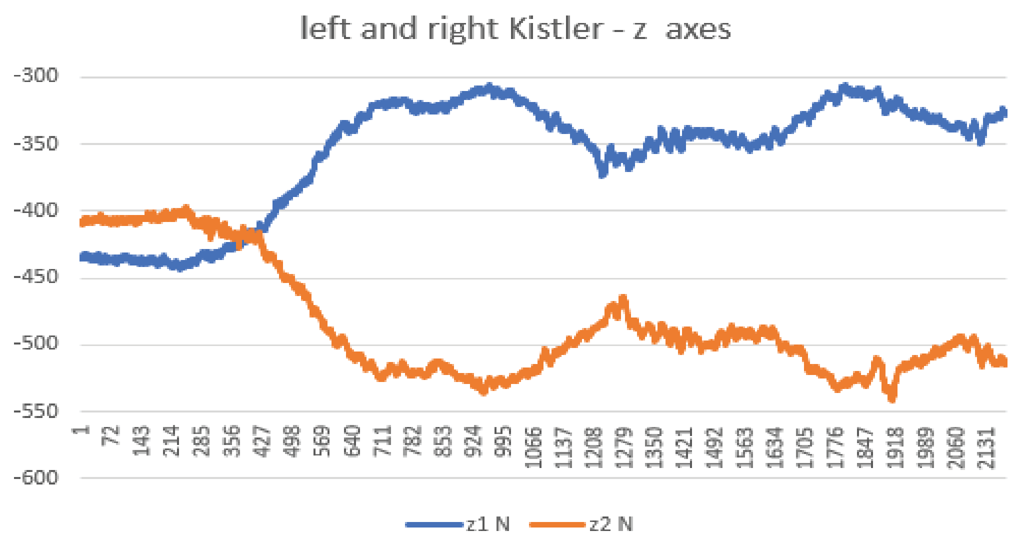

Figure 12: Z-axis (vertical force in Newtons) for left and right Kistler plates. Horizontal=frame, 200/sec

For the "z" axes, demonstrating separate right and left foot upward-downward forces and corresponding with weight shift between the feet, there appears to be clear connection, with relative weight shift from right to left foot as the instrument is raised, then some further shift **prior** to initiation of slide motion. This may represent some learned anticipatory balance shift in preparation for balance deviation about to be created by slide motion.

DISCUSSION

With multiple cameras producing and recording reflected infrared signals, it is common to have spurious reflections, or "ghosting" effects, which falsely suggest the presence of additional position markers – this can "confuse" the reconstruction software into creating incorrect data. For this trial, two sources of spurious reflections were determined: the metallic force platforms, and the reflective bell section of the trombone. These were controlled by covering the force platforms with wrapping paper, and the exterior of the trombone bell with a minimal-weight nylon sleeve, which had minimal impact on the instrument playing characteristics.

A second area of reflective marker “confusion” was produced by the density of marker placement, from close proximity of markers on the bell, left hand/wrist, upper trunk, and head, when instrument and subject were in the playing (versus instrument-down) position. This difficulty was lessened by reducing the marker number on the bell section from five to three. It was also found necessary to manually perform an electronic re-labeling for each of the instrument markers for each trial; the “auto-label” functionality of the Nexus software sometimes confused subject and instrument markers.

The study trial recording included a short period of time (initial 420 frames, 2.1 seconds) during which the subject raised the instrument to playing position. Presently, it is assumed that any overload contributing to injury relates more to actual playing, rather than from repetitively raising and lowering the instrument. Quantification of typical repertoire demand and player habit for ratios of resting versus playing position, with determination of typical number of instrument-raise motions for trombonists, may be of benefit for future study to verify this assumption.

The relative levels of joint excursion between the left and right upper extremities supported the earlier stated assumption that, during trombone performance, the left side is mostly subject to static loading with the right side featuring more dynamic activity. This asymmetry, coupled with the reported rates of symptoms by Chesky (2002), supported the pattern of relative risks from static versus dynamic activity in violinists noted by Visentin (2004).

The initial 420 frames also demonstrated a center of gravity shift as the instrument was raised. It is of interest that the shift toward the left was subsequently maintained throughout the duration of slide position changes rather than varying with alternating slide positions. Future studies with multiple participants will be required to demonstrate whether this is a general characteristic associated with the posturing necessary in managing this asymmetric instrument, or whether balance shifts relate more to individual performers' tendencies. Future explorations of patterns of balance shift and anticipatory balance changes could be of significant value, both in research that focuses on evaluating PRMD risks and in trombone pedagogy.

Motion capture technology and ground reaction measurements have long been used to improve outcomes and reduce injuries in high level athletic training. The data from this test-of-concept study strongly suggest a comparable role for these technologies in further study of trombone biomechanics. The next steps in trombone biomechanics research should include multiple-participant studies comparing joint ROM between players, gender, differing anthropometrics, ages, and playing-expertise levels. These will be of interest to establish biomechanical norms, and determine if deviation from those norms is a risk factor for the development of PRMDs. Finally, while this study explored biomechanical parameters associated with trombone playing while in standing position, a substantial portion of a musical performance activity occurs in a seated position; as such it may be valuable to for future studies to assess the same factors with regard to both standing and sitting positions. Ultimately, the outcome of such research could help take some of the "guess-work" out of injury prevention education, while facilitating pedagogy and improving the long-term vocational health and wellness of trombone performers.

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Abstract and poster submitted and presented to June 2021 annual PAMA symposium

CHAPTER 4: TITLE OF PRESENTATION: BIOMECHANICAL PARAMETERS IN THE STUDY OF PAIN RELATED TO PLAYING THE TROMBONE

ABSTRACT

There is a paucity of scientific and pedagogical literature regarding biomechanics, posture optimization, and balance, in playing the trombone. Among brass musicians, trombonists have high rates of playing-related musculoskeletal pain. Problems of the left arm are twice as common as the right.

Improved understanding of factors in left arm pain could result from kinematic and electromyographic (EMG) study of playing motions. This is a proof-of-concept study, the objective to assess the utility of Vicon motion capture, ground reaction force (GRF) measurement, and EMG in simultaneous data generation regarding balance and multi-segment body positioning, in various slide positions. Better prevention strategy for teachers, and treatment strategy for health care providers, is anticipated. This study involved inter-disciplinary collaboration between representatives of sport medicine, music performance/pedagogy, and kinesiology.

Keywords: trombone, posture, upper extremity, biomechanics, EMG

INTRODUCTION

There is little scientific and pedagogical literature regarding biomechanics, posture optimization, and balance, in playing the trombone. Trombonists have high rates of musculoskeletal pain, the left arm twice as common as the right. This one-subject proof-of-concept study assessed the utility of simultaneous Vicon motion capture (kinematics), GRF measurement (balance), and EMG (muscle activity), over various slide positions while playing. Future use of the methodology may provide biomechanical rationale for left arm pain leading to better prevention strategy forteachers, and treatment strategy for health care providers.

METHODS

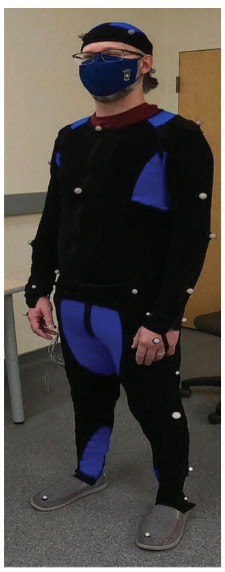


Figure 13: subject marker placements

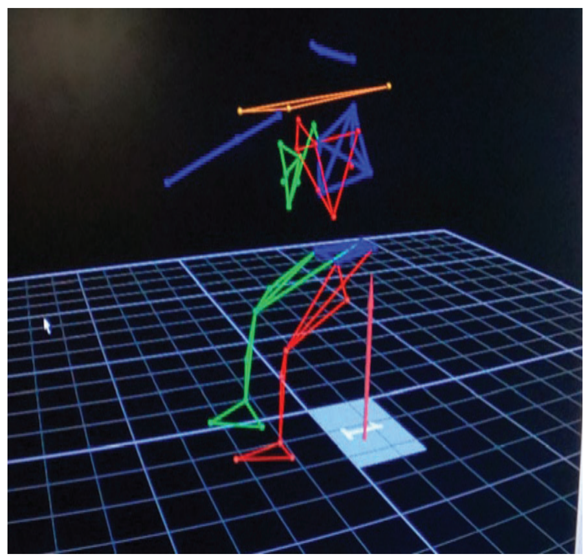


Figure 14: Vicon 3D re-creation of body and instrument segments

Electronic models, involving 39 infrared reflective human and 6 instrument markers, were established for Vicon data recording. The Vicon system utilizes ten cameras producing and recording reflected infrared light, allowing for a tri-angulated position record for each marker. Trials determined optimum camera positioning for clear marker recognition. GRF was measured via standard Kistler plate methodology, with EMG capture of four representative muscles of the left upper extremity.

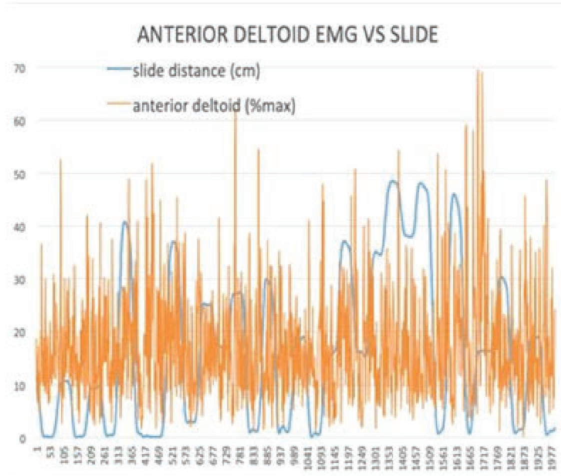


Figure 15: EMG lead placement - left arm/shoulder, anterior deltoid (% max voluntary contraction); slide motion

RESULTS

Utility of the technology for simultaneous generation of desired data while playing was confirmed for this single-subject study. Range of motion (ROM) data included three planes for shoulders and wrists, and one plane for elbows. Left shoulder angles were near-static, but did demonstrate some internal rotation and abduction change during right-hand reach to sixth slide position, with right shoulder showing more dynamic activity in flexion and internal rotation planes through-out, predictably mirroring slide motion. Ground reaction force demonstrated highest variability in lateral balance shifts, roughly corresponding to slide extension. EMG of the left upper extremity suggested primarily static activity, the wave form not showing a correlation with slide position.

Table 7

Left and right upper extremity joint position in degrees while playing. Parentheses indicate motion range

Joint	Side	Flexion-extension	Abduction-adduction	Rotation
Shoulder	Left	52 to 56 (4)	23 to 36 (13)	15 to 32 (17)
	Right	35 to 70 (35)	6 to 23 (17)	5 to 45 (40)
Elbow	Left	124 to 131 (7)	NA	NA
	Right	17 to 125 (108)	NA	NA
Wrist	Left	-23 to -1 (22)	18 to 48 (30)	14 to 73 (59)
	Right	-22 to 15 (37)	-5 to 62 (67)	62 to 145 (83)

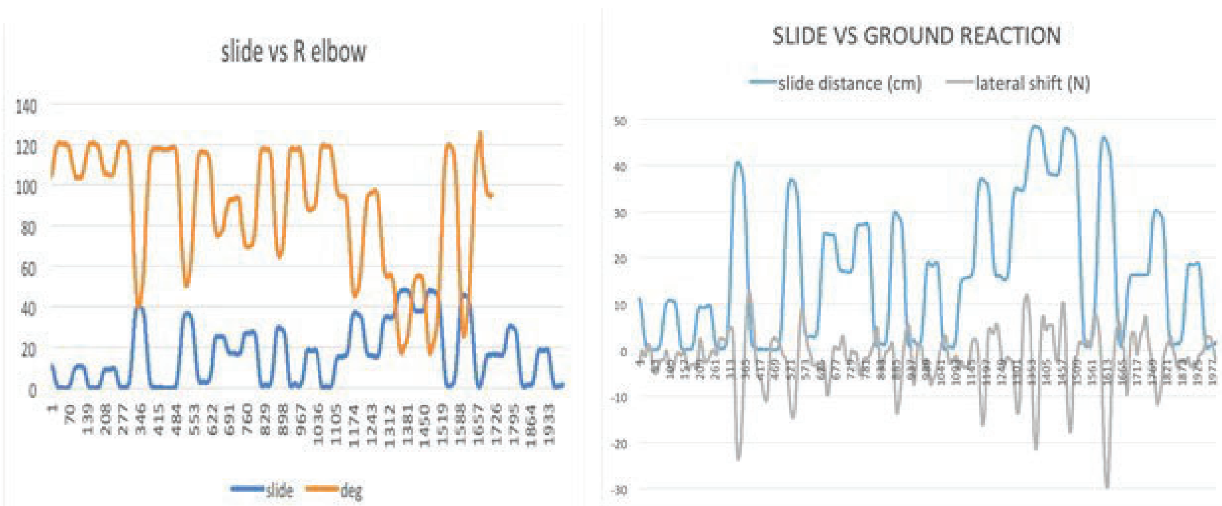
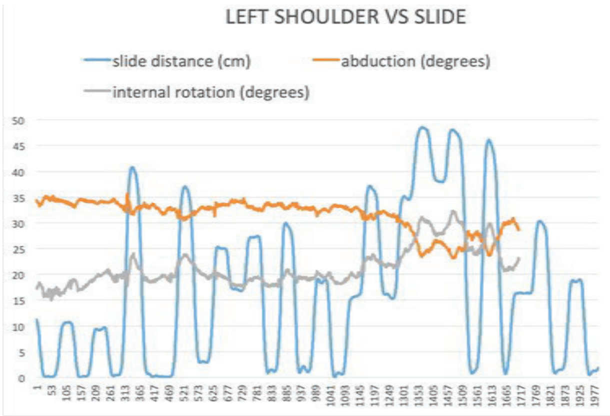


Figure 16: (L) Right elbow position and slide motion; (R) Lateral ground reaction force and slide motion. Horizontal=frame, 200/sec



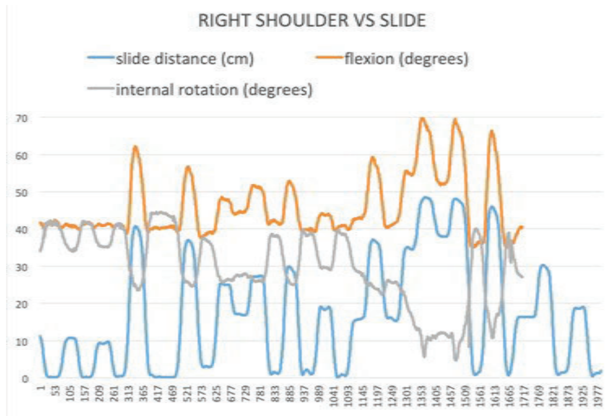


Figure 17: Left and right shoulder position and slide motion. Horizontal=frame, 200/sec

CONCLUSIONS

The results indicated a valid role for simultaneous multiple-modality data collection, in studying the biomechanics of trombone performance. Further trials involving multiple participants will establish biomechanical norms, with assessment for potential deviation as a pain risk factor, and evaluate varying playing postures and conditions for mechanical impact. EMG may outline characteristics of the higher pain risk forthe left (static) side relative to the right (dynamic) upper extremity. The influence of anticipatory and reactive balance shifting also may provide novel nuance for discussion.

This study involved inter-disciplinary collaboration between health, music performance/pedagogy, and kinesiology disciplines at the University of Lethbridge.

CHAPTER 5 – for submission to MPPA

A Comparison of Multiple Biomechanical Parameters in the Study of Left Upper Extremity Pain in a Small Population of Trombonists

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CHAPTER 5: A COMPARISON OF MULTIPLE BIOMECHANICAL PARAMETERS IN THE STUDY OF LEFT UPPER EXTREMITY PAIN IN A SMALL POPULATION OF TROMBONISTS

ABSTRACT

Prior study has indicated problems of the left arm as twice as common versus the right in trombonists, with the left arm static load postulated as a determinant for pain. While motion capture technology has demonstrated capacity to provide valid data regarding upper extremity joint angles, this modality alone does not fully reflect the degree of muscle load and activity. The addition of simultaneously collected electromyography (EMG) measures of left upper extremity (LUE) key muscle groups to the motion-capture and ground-reaction force data collection, has previously suggested utility. Prior single-subject study noted near-static left shoulder angles on motion capture, with LUE EMG also confirmatory for static activity with no clear relationship to slide motion. GRF data found variability mostly in lateral balance shifts, corresponding roughly to slide extension.

This study extended the methodology verification to a multiple-subject setting (n=7) to assess for general biomechanical characteristics associated with playing and bearing the weight of this asymmetric instrument. Evaluation for a relationship between balance tendencies, anticipatory adjustments, and playing-related pain was proposed, in addition to establishing norms for biomechanical parameters. The comparison of such parameters for players with differing genders, anthropometrics and ages, and examination for deviation from those norms as a risk factor for the development of pain, was included in planning. To guide the development of some precedent/standardized-approach for future biomechanical studies in trombonists, a comparison between the various biomechanical modalities in their variability and relative predictive value was proposed.

Utilizing the simultaneous data recording for multiple parameters, seven university-level trombonists each played a standardized etude in the motion capture lab of the University of Lethbridge. New components in this study included CoP (centre of pressure) evaluation, leading to quantification of Body Swing, allowing comparison between players for postural side-dominance, and degree of dynamic vs static postural tendency. Additionally, each player performed under varying playing "conditions" including seated vs standing posture, legato vs detached playing style, and use of valve as an alternative to 6th slide position. Pain history was introduced as a variable in the comparison of biomechanical variability between players.

Keywords: trombone, balance, upper extremity, biomechanics, EMG

INTRODUCTION

Brass musicians in general report significant playing-related musculoskeletal pain (PRMD), with trombonists noting prevalence rates up to 70% (Chesky et al., 2002) [1]. Problems of the left (primarily static) upper extremity (shoulder, forearm, elbow, and wrist) are twice as common as those for the (primarily dynamic) right side. An EMG (electromyography) study (Price and Watson, 2018) [2], noted that anterior deltoid, pectoralis and biceps EMG activity levels were all measured as higher for the left arm in trombone players. The LUE bears the weight of the instrument while playing, with the right mostly controlling slide motion during performance.

A better understanding of biomechanical factors, particularly the weight-bearing forces on the left arm and the shifting center of gravity while playing, may outline determinants leading to playing-related pain. Benefits could include effective prevention strategy for teachers, and better treatment strategy for health care providers.

This multiple-subject study (n=7) was structured to compare the biomechanical variability of multiple parameters, between players and playing conditions, and was anticipated to differentiate between general characteristics associated with handling this asymmetric instrument, versus balance shifts relating more to individual human-subject tendencies. Comparison of joint range of motion, patterns of balance shift, and anticipatory balance changes, between players of differing genders, anthropometrics, ages, and playing-expertise levels, will be of interest in defining biomechanical norms. Deviation from those norms is a hypothesized risk factor for the development of PRMDs.

Methodology verification for more significant biomechanical parameters or combination of parameters in trombonists was an expected outcome. The development of methodology involving the synchronous measure of core posture and left upper limb muscle activity was anticipated to provide insight. An additional biomechanical parameter not assessed in earlier trials, CoP (centre of pressure), was proposed for addition in this phase of study to assess body swing as a surrogate for postural activity.

The study proposal was reviewed and approved by the University of Lethbridge Human Participant Research Committee. It was anticipated that any accurate assessment of a relationship between biomechanics and pain would require some threshold quantity of playing activity and technical expertise. Purposive case sampling strategy was therefore implemented to identify seven participants (males=6, females=1), known to the research group or instructional faculty of the University of Lethbridge, as experienced, accomplished adult trombonists, each with current ongoing or past experience playing at a semi-professional or professional level and a current threshold playing frequency. Each consenting participant was booked for an individual two-hour lab session. Prior to the lab date, each participant completed a short paper-based demographic questionnaire documenting information regarding age, gender, history of playing-related pain, impact of pain on playing amounts or technique modification, number of years playing, quantity of playing, and instrument type (tenor vs bass). Participants were considered as experiencing pain if they answered “yes” to both of “have you experienced any recurring pain associated with playing in the last five years” and “do you believe the pain is caused by playing”. Due to the small population size and non-validation of the survey questions as a scientific tool, responses were not further broken down into laterality or assessed for statistical significance.

To maintain anonymity, each participant was assigned a 2-digit numeric code, the code generated by unrelated random number generator software, with each referred to in data recording and reporting as either “participant” or “subject ##”.

Table 8

Participant age range and pain location

Participants	Participant identifier codes	Age range	Gender	Pain (total)	Shoulder Pain	Arm Pain	Back Pain
7	13, 30, 33, 46, 86, 89, 98	22 – 63	Male=6 Female=1	4	3	3	2

Similar to literature reports regarding musician-perception regarding pain etiology (Ackermann and Adams, 2004) [3], over half of the participants reported pain believed to be caused by playing. Wrist, elbow and upper arm pain reports were grouped into a single category as "arm pain." Many reported more than one site of pain. Shoulder was the single site most commonly reported.

Table 9

Participant breakdown of pain, playing history and instrument weight

Pain History	Mean Years Playing	Mean Age	Mean hours/week	Mean instrument weight
No	40.3	53.3	3.0	4.7
Yes	24.5	37.5	10.3	5.8

Breakdown into pain and no-pain groupings did suggest potential interesting trends. Increased age and increased number of years playing did not show an association with pain. Higher number of hours played per week, and heavier instrument/double-valve use in the predominant instrument type played, did however, have association with increased pain reporting.

METHODS

Lab sessions occurred over a one-week period in November 2020 in the Kinesiology Department motion capture lab of the University of Lethbridge. Participants had been informed one week prior to the sessions, of the detailed lab session process, equipment to be used, and parameters being measured. All participants understood that the study was to assess biomechanics only, and would not evaluate musicality or performance quality. On arrival for the lab session, each participant was given an orientation to the lab and research team.

Data Collection

Preparation involved the placement of 6 reflective markers placed on each participant's instrument, 39 reflective markers per human subject, and 9 EMG pads on the left shoulder and upper arm. Jackets, arm/leg/head bands, and gentle (wig maker) adhesive double-sided tape were used for marker placement. The participant was offered after a warm-up session with all data collection equipment in place.

Each participant was then (initially) seated, the chair placed on a single Kistler GRF platform. A standardized (approximately) 45 second etude was utilized, chosen and edited by the researcher for representative slide position variety, and of difficulty level suitable for performance without advance rehearsal. All players were allowed a run-through to familiarize and acclimatize to playing in the lab setting.

With the simultaneous recording of whole body and instrument position/motion data via Vicon Nexus 1.7.1, LUE EMG, and GRF (single Kistler plate), the etude was performed under varying playing conditions. EMG (muscle force) evaluation was limited to the LUE. Repeat performances for any playing condition were permitted if the participant desired, or if there were obvious gaps in the data stream or missing marker data. For most conditions and participants, multiple takes were recorded. Playing conditions for which data were collected are outlined in figure 18. Players of instruments equipped with an F valve, were asked to replay the etude, the additional performance allowing valve use as an alternative for the 6^{th} slide position. Data was collected in four biomechanical categories, outlined in figure 19. Participants were not aware of the specific musical phrases recorded – technical staff recorded 2 excerpts from the etude, the segments chosen reflecting contrast between detached and legato playing style, both well within the body of the etude, to avoid postural or other position changes inherent to starting and finishing a musical performance. Each excerpt was approximately 9 – 10 seconds in length.

	detached	legato	valve
seated	+	+	+
standing	+	-	-

Figure 18: playing conditions. "+" indicates data collection

Area/measure type	Playing condition	Report coverage	Data reported
Left upper extremity – motion capture - joint angles 7 subjects	Multiple: • seated detached • seated legato • standing • valve	• neck (3 axes) • shoulder (3 axes) • elbow (1 axis) • wrist (3 axes)	• mean/SD of *angles* (degrees) for each player, each condition • data breakdown for slide zone
Left upper extremity – EMG 6 subjects	Multiple: • seated detached • seated legato • standing • valve	• trapezius • posterior deltoid • anterior deltoid • extensor carpi	• mean/SD of *%MVC* for each player, each condition • data breakdown for each slide zone
Ground reaction force – single Kistler force plate 7 subjects	seated, detached only	• anterior/posterior (X axis) • lateral (Y axis)	Plot: • X and Y axis *(force in Newtons)* against time • slide extension against time
CoP (Centre of Pressure)– from Vicon processing of GRF and pelvis position 6 subjects	seated, detached only	• CoP - ant/posterior (X axis) and lateral (Y axis) • Total body swing	• mean CoP (mm) in X and Y axis • CoP range each axis • total body swing

Figure 19: biomechanical data categories

Data Processing

Data was evaluated and processed over a several month period between December 2020 and May 2021. The choice of which recorded take was selected for further data-processing was driven primarily by the varying quality of the motion-capture data between takes. The number of infrared sensors (46) and cameras, with the presence of a reflective instrument, does create significant potential both for missing data points and spurious reflections, requiring careful manual data cleanup, and use of Nexus (approved) protocols for fill-in of missing segments. Ankle and wrist markers on some participants were particularly prone to data loss. Once motion-capture data reliability and processing determined data-acceptable trials, EMG, GRF and CoP data from those specific trials were processed further. In some instances, inadequacy of the EMG data resulted in a subsequent choice of an alternate motion capture trial, for which data was adequate in both realms. For one participant, the recorded MVC trial data was insufficient to provide an accurate denominator for %MVC calculation, so EMG data was processed further for only six participants. For another participant, the motion capture and EMG data were good quality, but an (as yet unidentified) model processing problem prevented CoP output, resulting in CoP assessment for only six participants.

Joint angles - data handling (7 participants)
Each participant, playing condition – data at 200 frame per second - determine slide extension, multiple body segment joint angle
Master data table in Excel
Pivot table function in Excel to extract summary tables (condition, mean, standard deviations, pain vs no pain, etc.)
Data not evaluated for statistical significance

Figure 20: joint angle data procedure. n=7

EMG – data handling (6 participants)
Raw data collection included maximum voluntary contraction (MVC) determination for each lead (3 consecutive maximum contractions against resistance) and playing trial data for each condition
Collection frequency at 1000 frames per second - data filtered/smoothed through Origin software
From smoothed data, 3 peaks of MVC were averaged for each lead

Smoothed trial data divided by the relevant averaged MVC to calculate % MVC for each trial
Master data table – Excel – reports mean and standard deviation of %MVC for each trial condition
Pivot table function - to extract summary tables

Figure 21: EMG data procedure. n=6

GRF – data handling (7 participants)
Collection via Kistler plate under bench (seated condition) or feet (standing condition)
Collection at 1000 frames per second – calculated average of each consecutive five frames to match slide excursion data of 200 frames per second
Plot X axis (anterior-posterior) and Y axis (lateral) for balance shifts during slide motion
No processing of Z axis
Evaluate (visually) both X and Y baseline relative to neutral
Evaluate (visually) for relationship between X and Y vectors and slide motion

Figure 22: GRF data procedure. n=7

CoP - data handling (6 participants)
Vicon produces CoP data based on pelvis position markers and GRF vectors
Collected at 200 frames per second, reports on X, Y and Z axis
Scatter plot of CoP X axis versus Y axis for each performer provides visual representation of balance swing during trial
Min, Max, Mean (and standard deviation) determination for CoP in X and Y axis via Excel
Total swing calculated via Excel
Pivot table function – to extract summary tables

Figure 23: CoP data procedure. n=6

RESULTS

Joint angles from Vicon Nexus Motion Capture

Joint angles were determined by the software for multiple body segments. For the purposes of this study, the resulting data was compared further for the LUE, including neck, shoulder, elbow and wrist. The standard deviations over the trial length for each studied joint angle axis within participants were low, in keeping with the assumed primarily static activity for LUE; mean data for each axis were therefore assumed to be an accurate comparator between participants.

Comparison of mean LUE joint angles between varying playing conditions (detached, legato, valve-allowance, and standing-detached) found minimal variance, suggesting doubtful significance of playing condition as a risk factor for pain. Similarly, comparison of joint angles during maximal (6th position) versus minimal (1st position) slide extension also noted minimal variance.

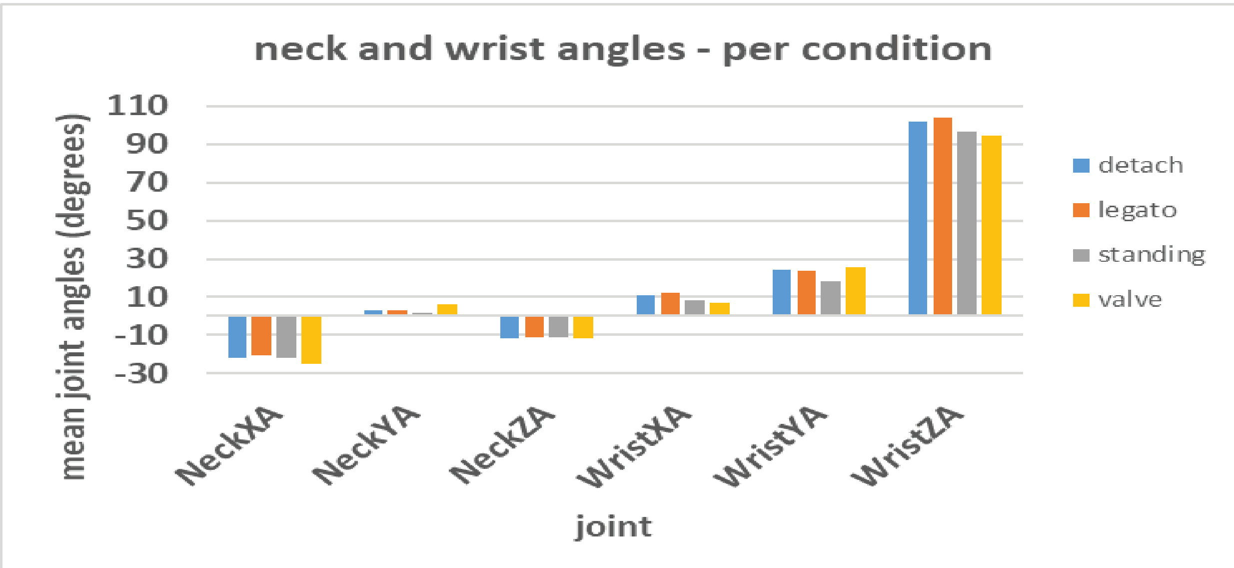


Figure 24: mean neck and left wrist joint angles per playing condition

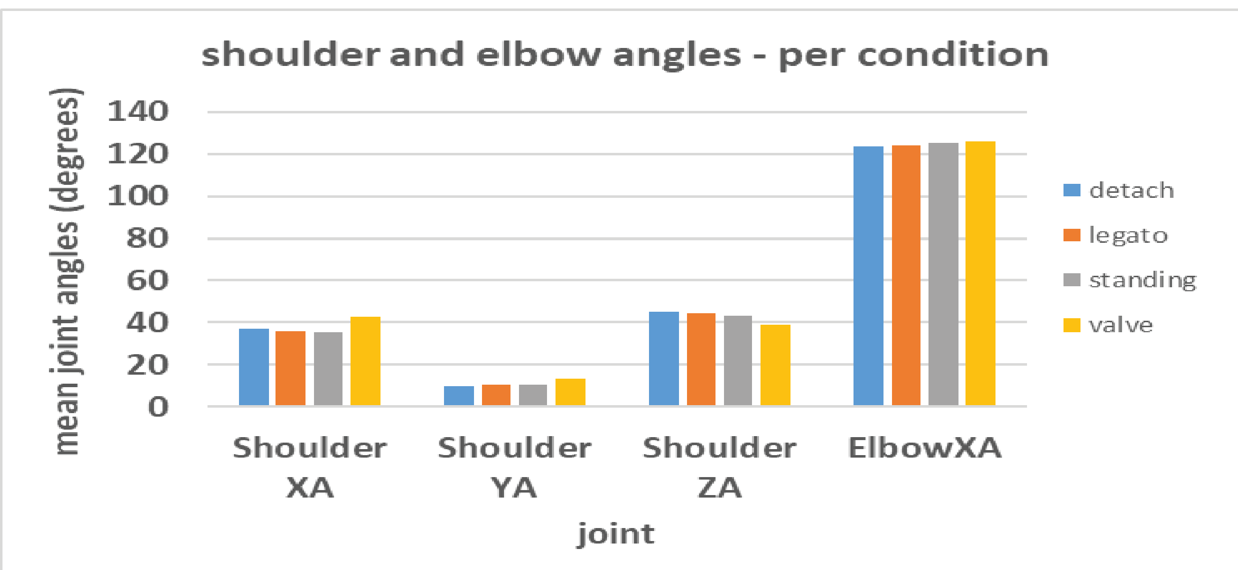


Figure 25: mean left shoulder and elbow angles per playing condition

Mean joint angles were compared between participants. For each joint axis, the magnitude of variation was reflected by the total range (distance between maximum and minimum means per axis). It was suspected that joint axes demonstrating higher biomechanical diversity may have more significance in evaluating each as a potential pain risk factor.

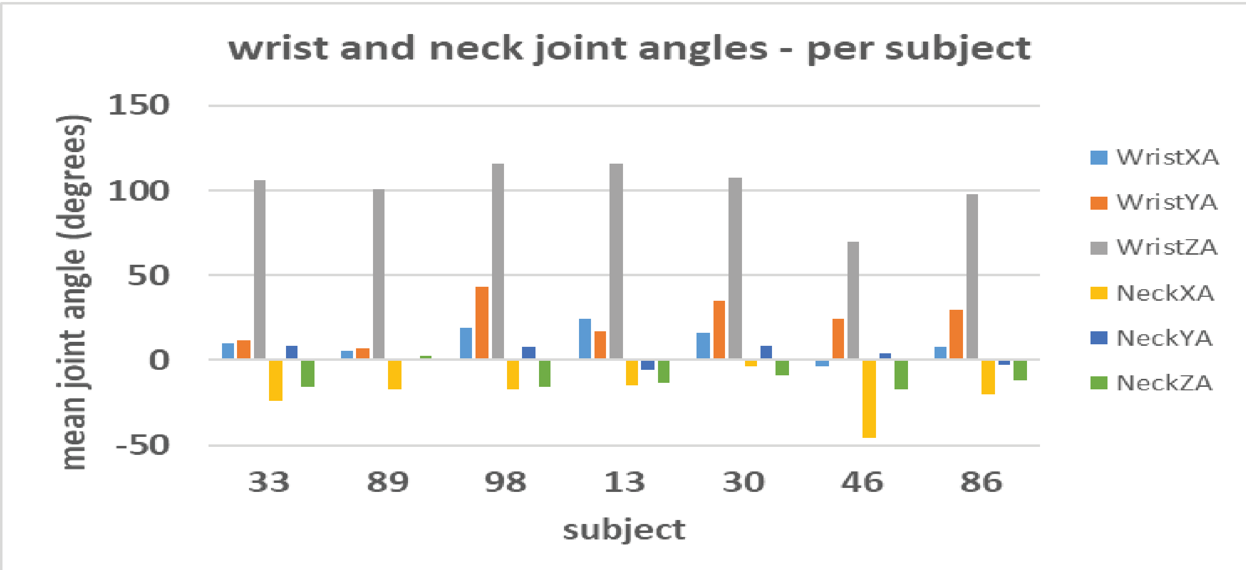


Figure 26: mean wrist and neck angles per participant. n=7

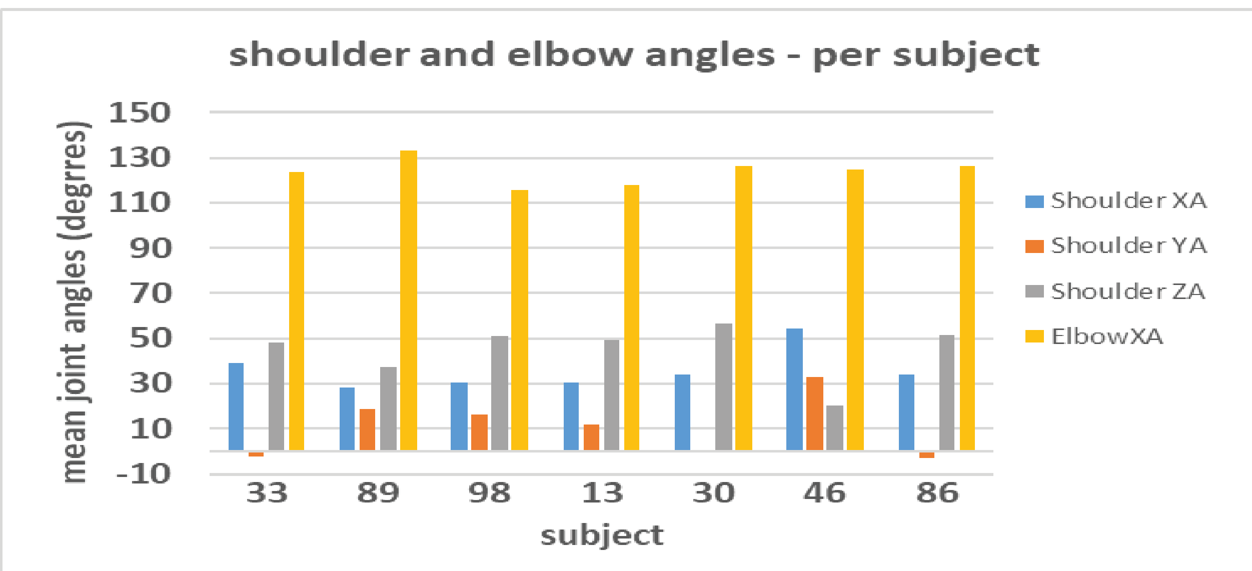


Figure 27: mean shoulder and elbow joint angles per participant. n=7

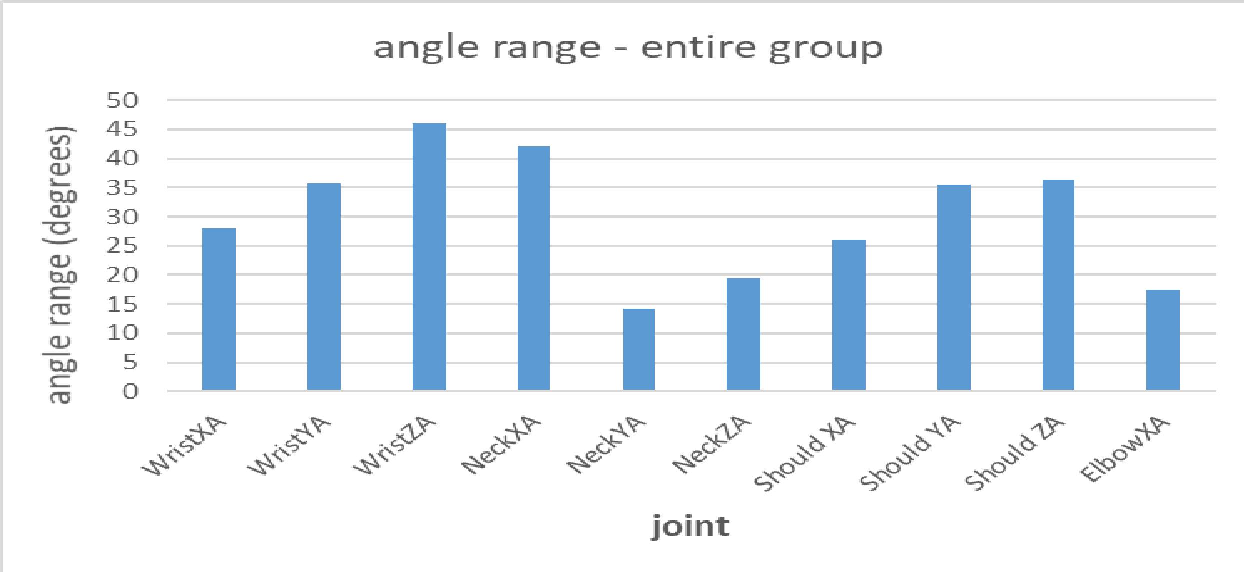


Figure 28: range of mean positions per joint across all participants

Variability of angle means between all participants was higher (above 20 degrees) for all wrist axes, neck XA, and all shoulder axes. Elbow variability was minimal. These findings are not surprising given the mechanism of holding and playing the instrument. A fixed degree of elbow flexion to grip and position the instrument at the embouchure leaves little chance for individual elbow variability. Degree of neck flexion, reflected in the X axis could vary substantially depending on the individual player tendency for degree of downward angulation of the overall instrument, with somewhat less likelihood for variation in lateral neck flexion (Y axis) or neck rotation (Z axis), in the typical tendency to hold the instrument straight forward. Forward flexion of the shoulder (X axis) would have less variability, similar to elbow flexion, given the need to grip the instrument to position the mouthpiece at the embouchure – any variation here likely reflects variability in arm length. Positioning the instrument at the embouchure could however be achieved over a variety of degrees of shoulder abduction (as reflected in shoulder Y axis data) and rotation (Z axis) with wrist compensation at the instrument.

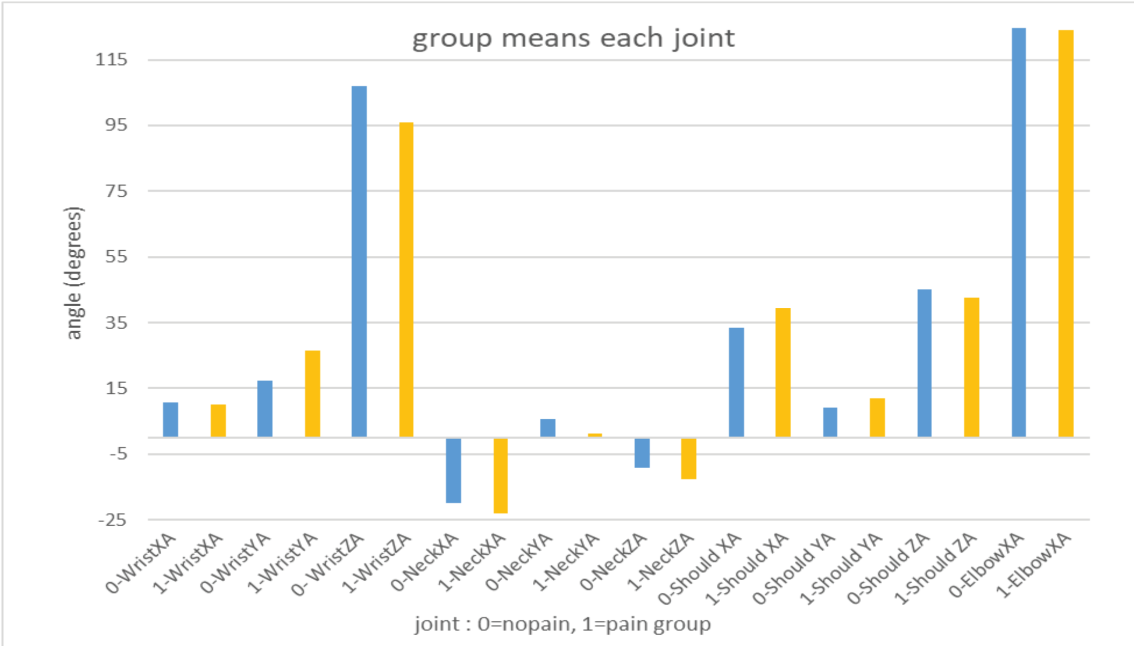


Figure 29: means difference (degrees) between pain and no-pain group at each joint axis

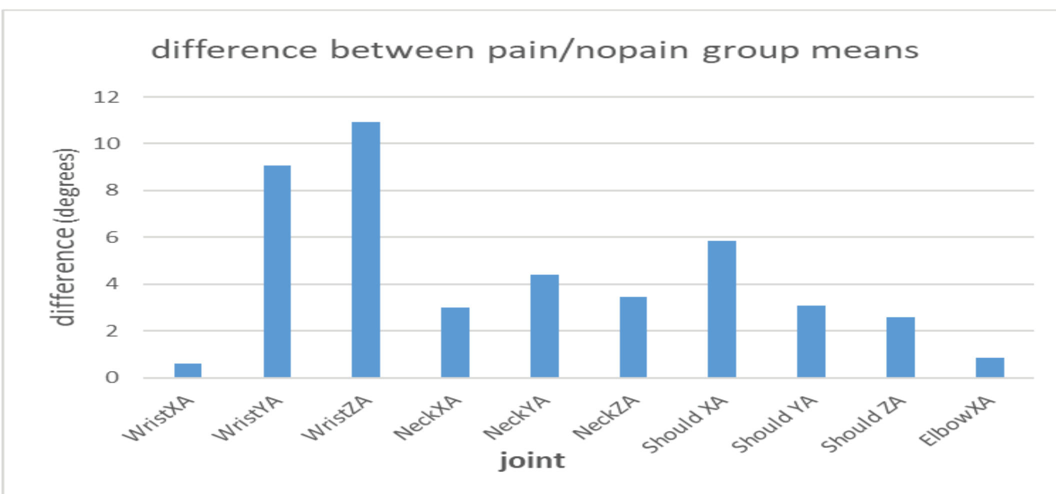


Figure 30: angle for each joint and axis, pain vs no-pain

Highest difference between pain and no-pain group means are for wrist YA and ZA, neck YA, and shoulder XA. Joint axes indicating both high overall biomechanical variability AND higher contrast between pain/no-pain groups were wrist YA and ZA, and shoulder XA.

EMG

Based on the joint angle determination of high inter-participant variability in static neck flexion, left shoulder abduction/rotation, and left wrist (all axes), EMG was utilized to check whether the angle variabilities were matched by variability in static muscle activity. There are technology limitations in making direct comparisons. Surface (skin-electrode) EMG was utilized, this technology not highly selective for specific muscles, potentially averaging electrical activity from multiple adjacent muscles. For wrist activity, only the extensor carpi area was practical to measure with this technology, this reflecting wrist flexion-extension, but not rotation or abduction-adduction muscle activity. None of the areas available for skin-electrode EMG evaluation were truly specific to neck muscle activity – the trapezius activity measured was lower trapezius, likely more related to scapula elevation than neck per se.

Abbreviation	Muscle	Function
TRAP	trapezius	Shoulder elevation
AD	anterior deltoid	Shoulder flexion and abduction
PD	posterior deltoid	Shoulder extension and abduction
EC	extensor carpi	Wrist extension

Figure 31: EMG muscle abbreviations and function

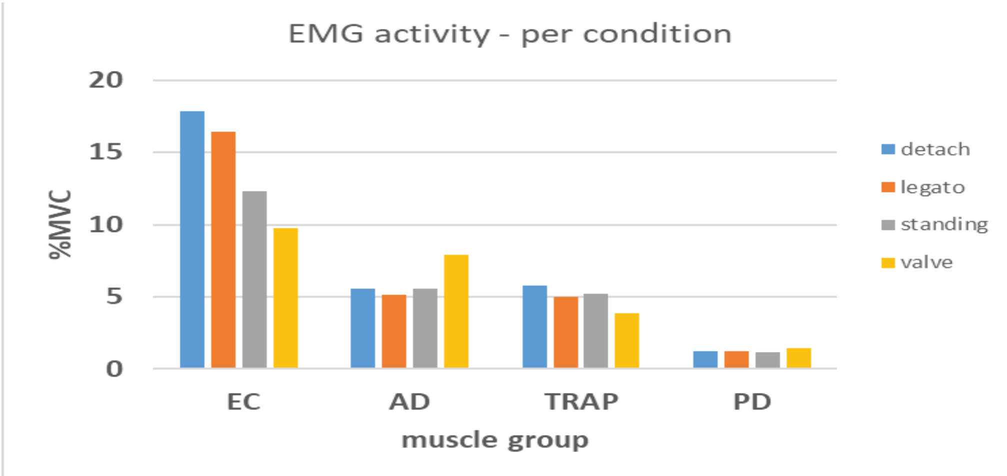


Figure 32: EMG activity comparison - between playing conditions

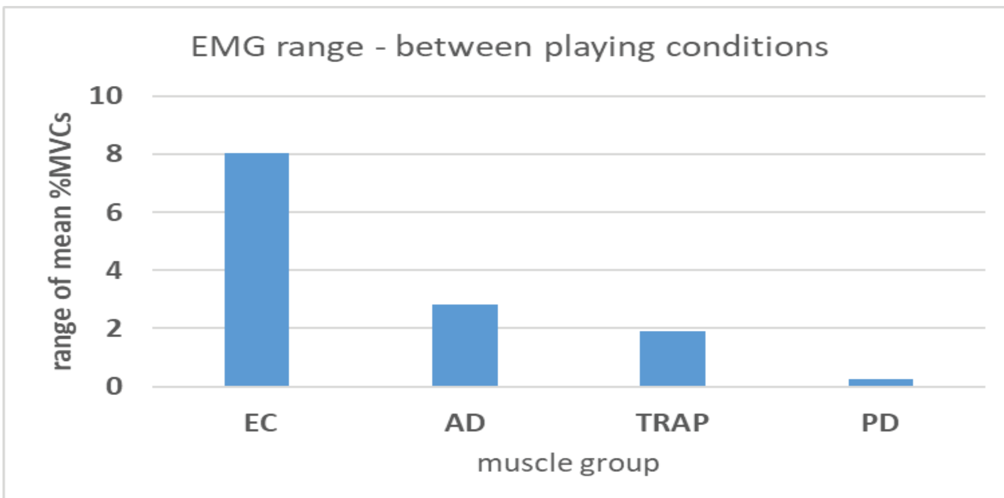


Figure 33: EMG range for each muscle group from varied playing conditions

Unlike static joint angle measures where there was minimal variability over the differing playing conditions, EMG evaluation was suggestive, particularly for extensor carpi and anterior deltoid, of varying static muscle activity by some conditions. One could surmise that wrist extensor activity needs to be greater when a trombonist is reaching out to 6^{th} slide position, to maintain stability of the instrument against the embouchure, accounting for the demonstrated reduced activity when valve use is allowed during the etude (allowing the same note to be played in 1^{st} position with no slide extension). It is also proposed that the increased anterior deltoid activity in trials allowing valve use reflects shoulder compensation for some force re-distribution in supporting the weight of the instrument while the thumb is required to function more independently from grip, allowing valve operation.

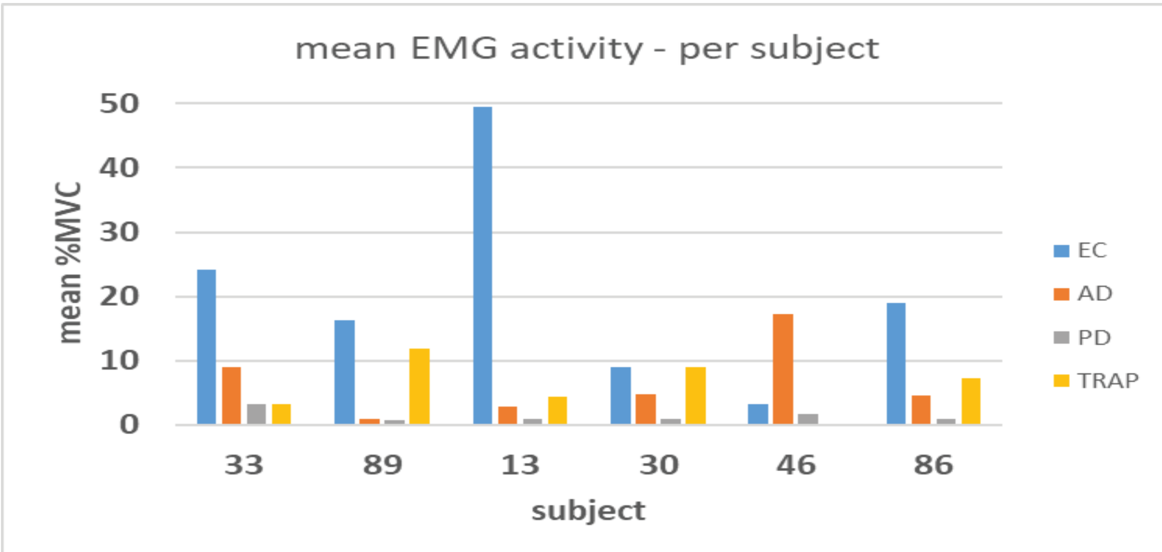


Figure 34: EMG activity by participant (n=6) and muscle group

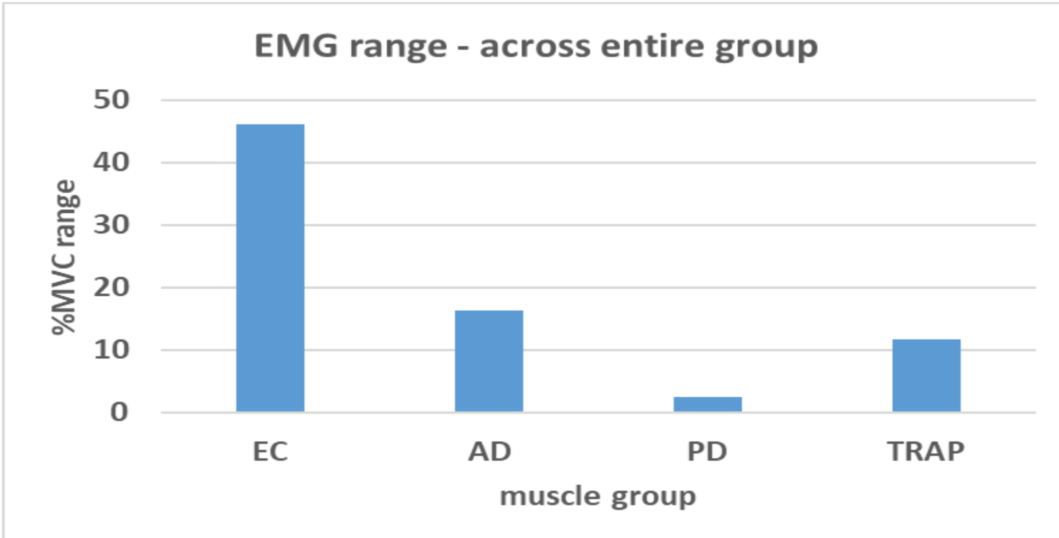


Figure 35: range across participants for each muscle group

Comparison between participants also demonstrates highest variability for the extensor carpi and anterior deltoid groups, this in keeping with the previously noted variability of joint angles for shoulder abduction with presumed compensatory wrist positioning. Joint angle measures did not assess shoulder elevation per se, however the trapezius EMG activity suggests some variability, supportive of an assumption that both left shoulder elevation degree and static load, could vary between trombonists, more so than shoulder flexion and elbow flexion as previously noted.

Potentially suggestive that variance in static muscle activity may be a risk factor for pain, the mean %MVC difference between pain and no-pain groups is higher for extensor carpi, anterior deltoid and trapezius. The pattern of variance relative to whether the various muscle groups demonstrate higher or lesser activity in relation to pain history is less clear.

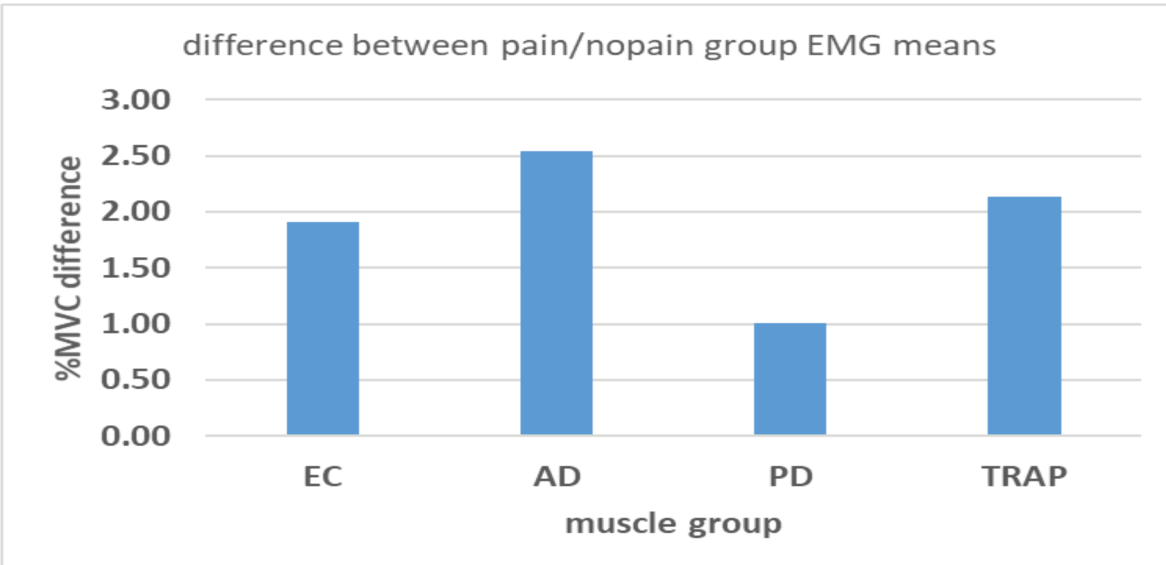


Figure 36: difference between group means for no-pain and pain groups each muscle area

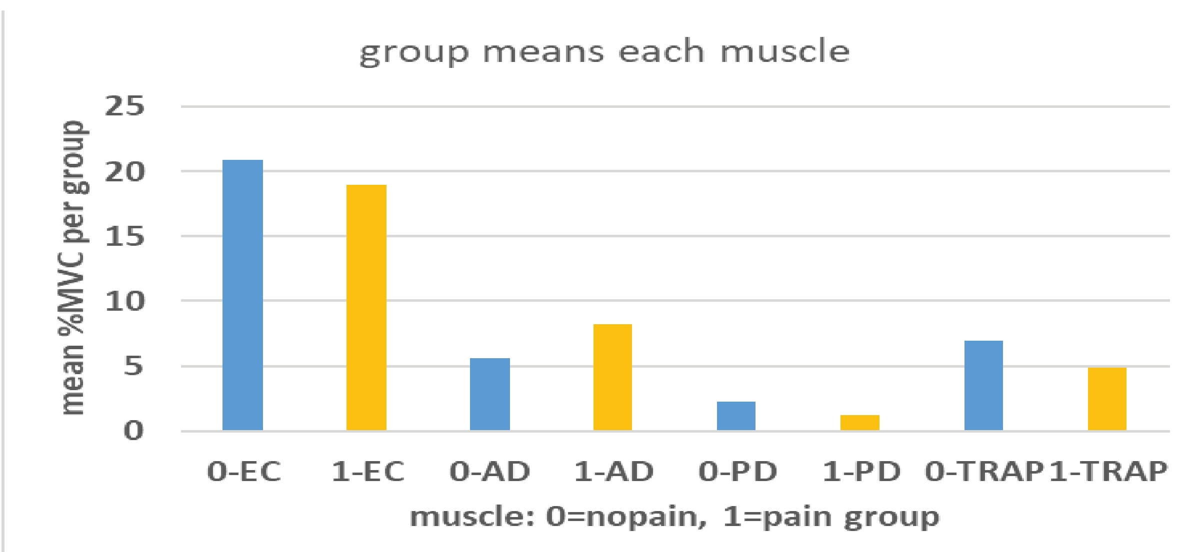


Figure 37: comparison of mean %MVC for pain and no-pain groups, each muscle area

Per individual participant – between playing conditions	Mean of participants – between playing conditions	Between participants
Participants 13, 33 – show wide EC variability (less activity in standing)	EC variability – large range	EC variability – large range
Participant 30 - shows wide trap variability (less activity in legato)	TRAP and AD variability – modest range	TRAP and AD variability – modest range
Participant 46 – shows minimal variability across all conditions	PD variability – minimal range	PD variability – minimal range

Figure 38: EMG variance

subject	Prominent muscle group (>10% MVC on EMG)
46	anterior deltoid
89	trapezius
33,89,13,86	extensor carpi

Figure 39: prominent EMG activity compared to other participants

Most participants demonstrated at least one area of clearly higher %MVC relative to other muscle groups. Only participant 30 had no muscle group demonstrating %MVC exceeding 10%; only subject 89 had more than one muscle area exceeding 10%. There is no apparent association between specific muscle group prominence and pain history.

Ground Reaction Force (GRF)

There are potentially two postural sources likely to contribute to variance in static muscle load for the LUE. One is the player-preferred LUE posture in holding the instrument, with evidence of variability in degree of shoulder abduction, neck flexion, and compensatory wrist posture as noted above. A second factor may arise from the overall body posture and degree of postural change while playing (CoP swing), this likely to influence the load of supporting the instrument to the embouchure.

The Kistler GRF plate measured the anterior-posterior and lateral forces demonstrated by the seated (and subsequent standing) participant while playing an etude (detached style), to assess direction and magnitude of truncal postural forces. It was assumed that slide extension would influence balance forces.

For all participants, a plot of the slide extension was included with a plot of the X or Y axis (force in Newtons), to visually assess for a postural relationship with slide motion. Figure 41 is an example of one-such X-axis plot vs slide (participant 30), this strongly suggesting an inverse relationship. Figure 42 summarizes X-axis findings for all participants. There is significant variation in the positivity vs negativity of the X-axis baseline, and positive vs inverse relationship with slide extension, between participants. Presumably, subjects differ in the compensatory mechanisms utilized to accommodate balance shifts created by slide motion.

Axis	Orientation	Direction (Force in Newtons)
X	anterior-posterior	more positive = forward force
Y	lateral	positive=right force; negative=left force

Figure 40: ground reaction force (GRF) axis explanation

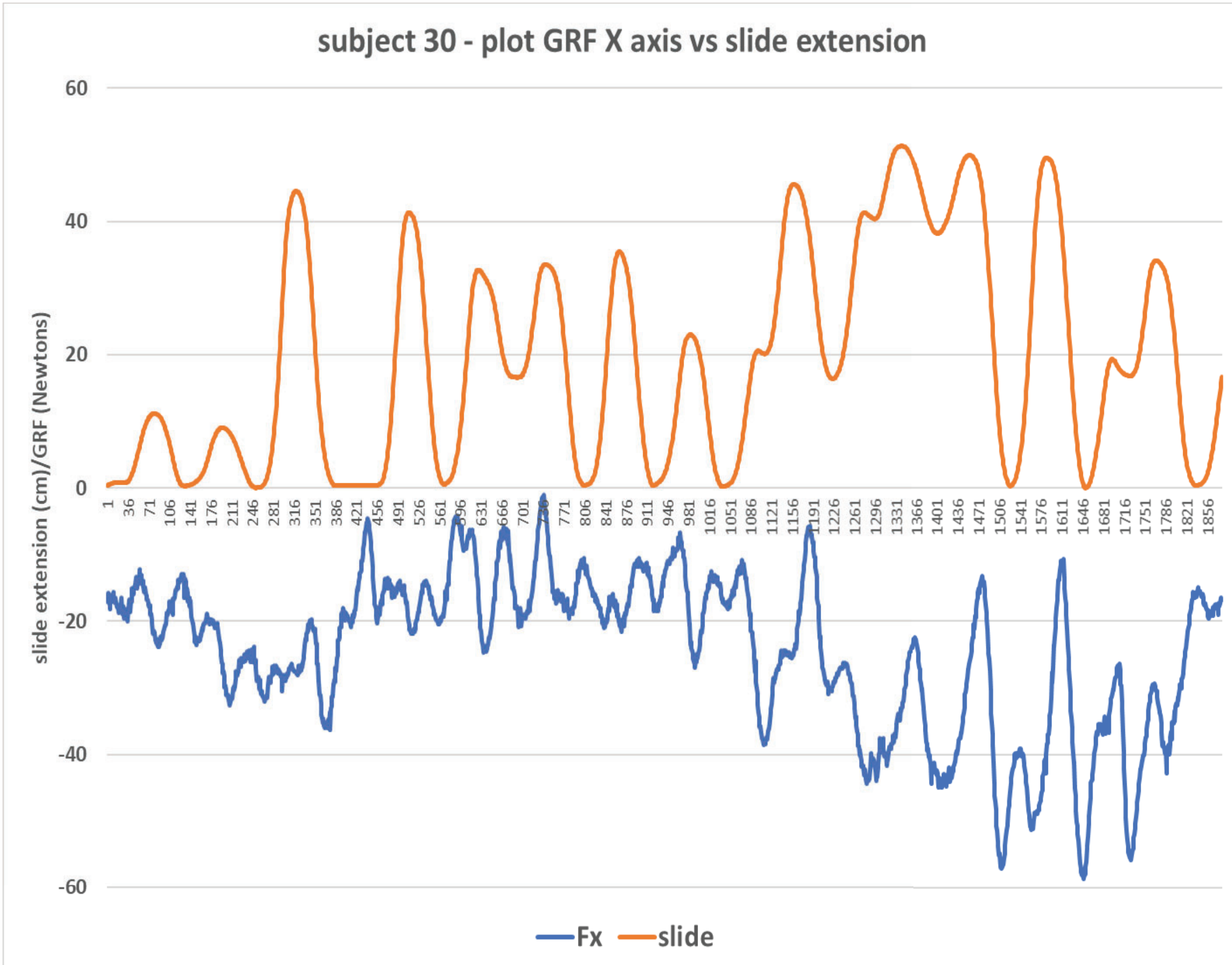


Figure 41: GRF X axis (N) and slide extension (cm) over 9 second etude performance. Horizontal=frame, 200/sec

GRF – X axis – compare between subjects	Relationship to slide motion (visible impression)
• Baseline mostly positive – 3 subjects • Baseline mostly negative - 3 subjects	• Positive correlation – 3 subjects • No apparent correlation – 1 subject • Inverse correlation – 2 subjects

Figure 42: GRF X axis observations. n=6

Figure 43 shows an example Y-axis plot vs slide (participant 46), this also suggestive of an inverse relationship. Figure 44 summarizes the findings for all participants. Here, there is suggestion of neutral to leftward postural forces as a baseline, with increased left shift during slide extension for most subjects. Y-axis variability is therefore doubtful as a contributing risk factor for pain.

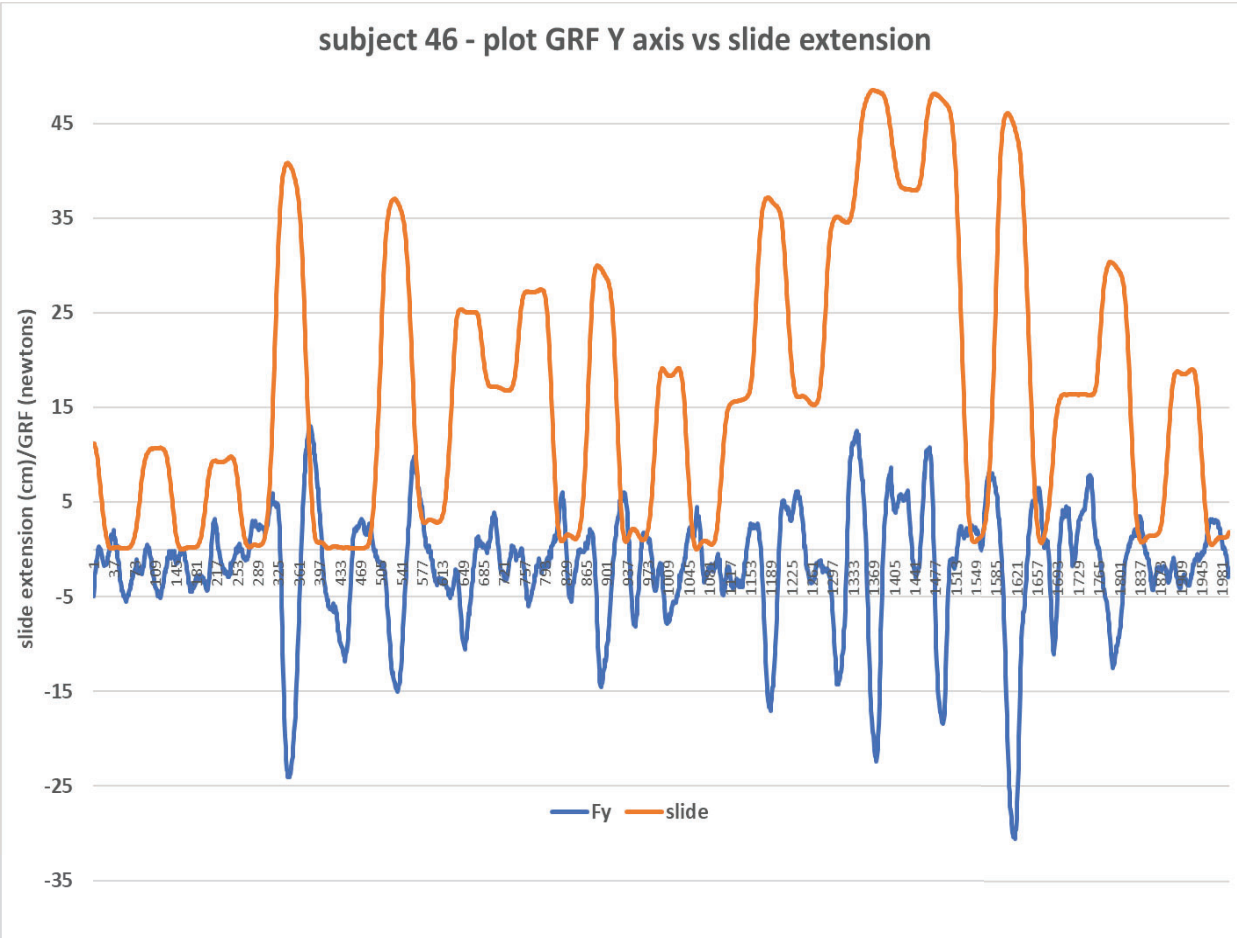


Figure 43: GRF Y axis (N) and slide extension (cm) over 9 second etude performance. Horizontal=frame, 200/sec

GRF – Y axis – compare between subjects	Relationship to slide motion (visible impression)
• Baseline mostly positive – 1 subject • Baseline mostly neutral – 2 subjects • Baseline mostly negative – 3 subjects	• Positive correlation – 0 subjects • No apparent correlation - 1 subject • Inverse correlation – 5 subjects

Figure 44: GRF Y axis observations. n=6

Comparing mean X and Y GRF axis values between participants does indicate high standard deviation, but the means of X-axis values do differ substantially between the no-pain and pain groups, while Y-axis means are not suggestive for any trend. The data suggest that an increased anterior postural force is associated with a lower pain history incidence.

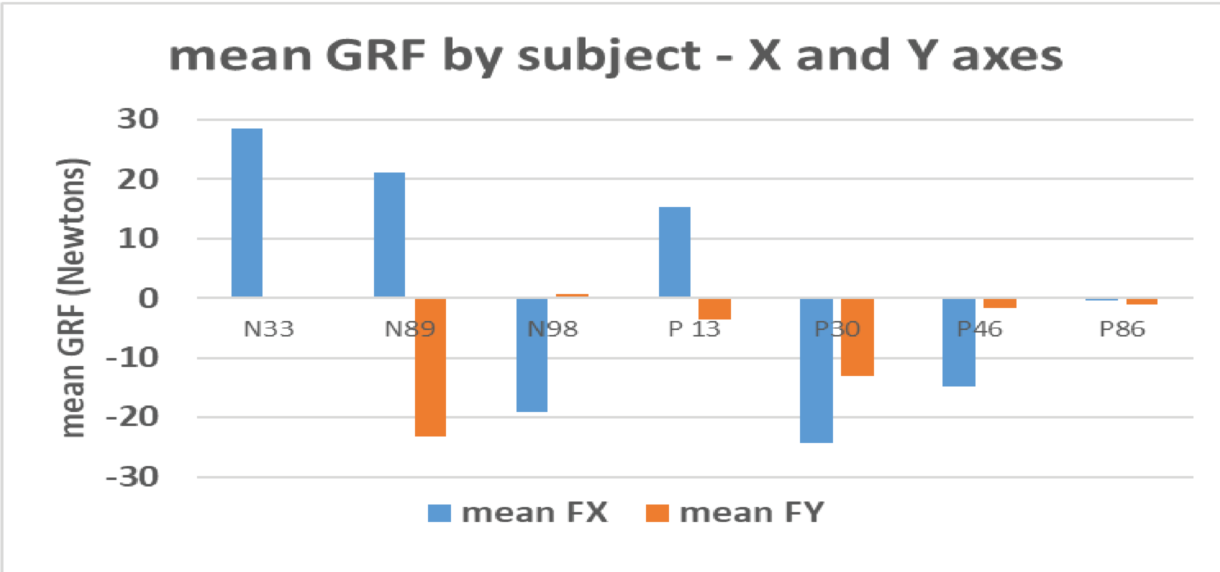


Figure 45: mean GRF over etude, for X and Y axis. (n=7). N=no-pain group (n=3), P=pain group (n=4)

Table 10

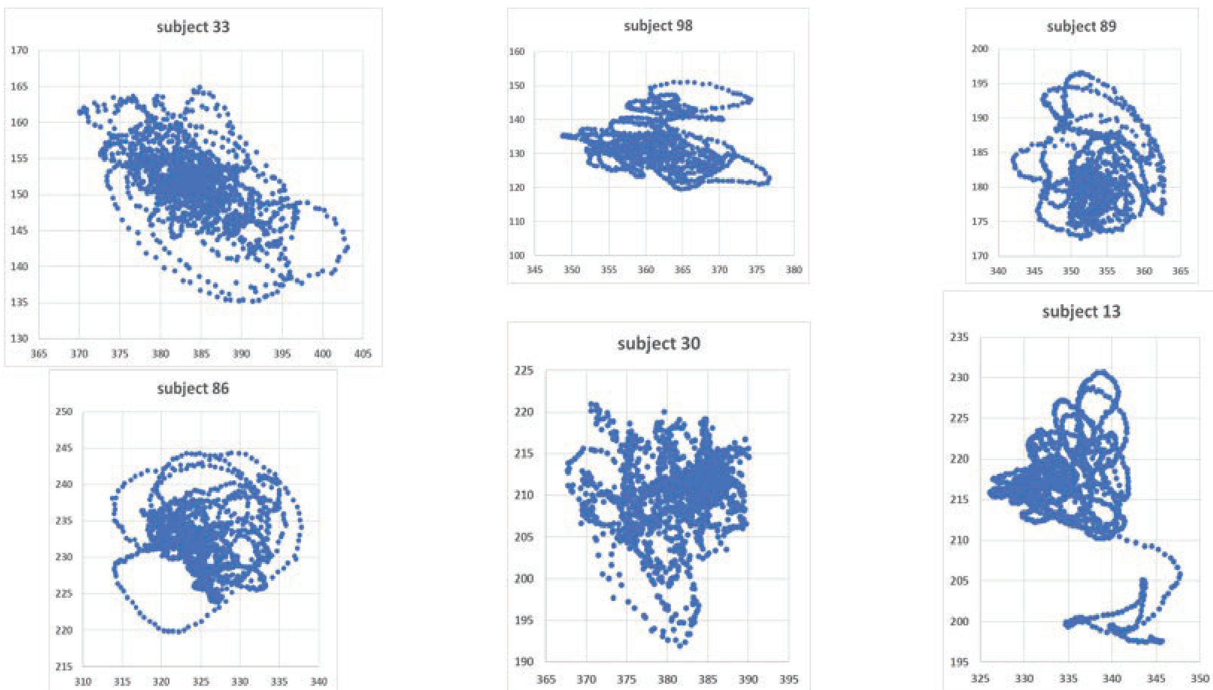
Comparison of mean GRF and standard deviation between no-pain (N, n=3) and pain (P, n=4) groups

Pain Group	Average Fx	Average Fy	Fx StdDev	Fy StdDev
N	10.13	-7.41	25.65	133.62
P	-6.02	-4.89	17.33	5.57

Center of Pressure (CoP)

An additional output from Vicon Nexus technology is the Center of Pressure (CoP), which represents the geographic point position on the force plate (2-dimensional) for the center of gravity, as determined from GRF and truncal position data, per frame. This indicator has potentially greater significance in balance perspective than raw GRF orientation.

Figure 46: CoP X vs Y per participant. n=6. Gridlines represent 5 mm increments. Top row is no-pain group.



Bottom row is pain group

Plotting X vs Y for each participant shows the varying CoP positions over the etude performance. Subjects differ both in the baseline center, amplitude and orientation of the range of CoP, as represented in figure 46. The visual comparison of these plots provides no clear suggestion of a relationship between CoP trends and pain history.

To assess further, the mean CoP per participant, and per pain/no-pain group, was determined for each axis. The data suggest higher mean Y-axis CoP values (more rightward) in the pain group. There is less overall variability between all subjects for the X axis CoP values.

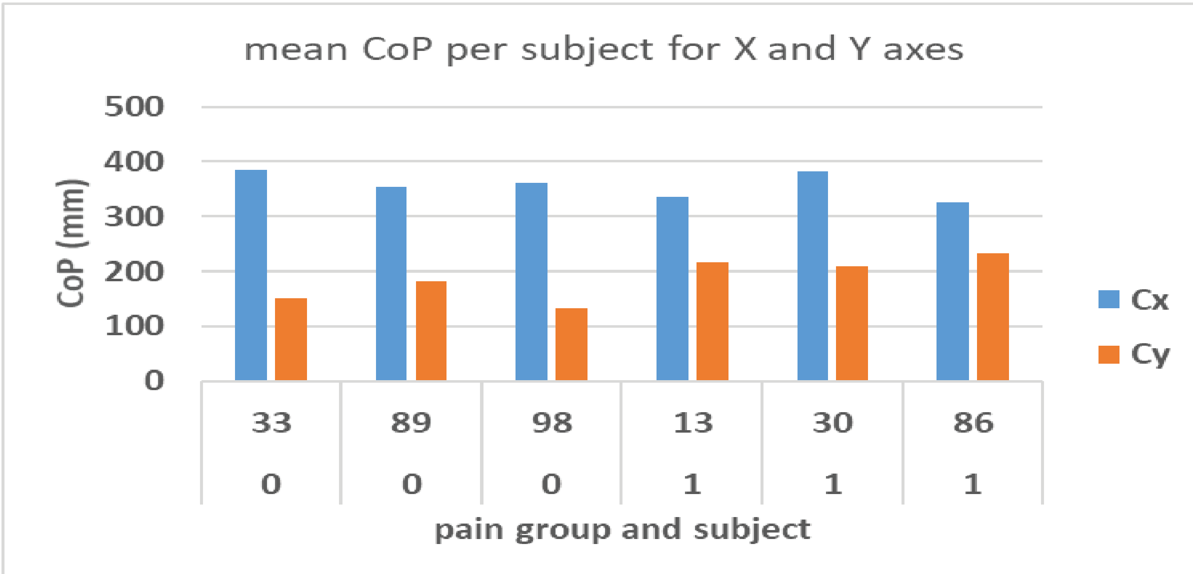


Figure 47: X and Y axis mean CoP per participant. 0=no-pain group, n=3; 1=pain group, n=3.

group	mean CoP - X	SD - X	mean CoP - Y	SD - Y	swing	SD -s
no-pain	366.34	16.10	154.98	24.42	1080.67	203.49
pain	347.08	30.19	219.77	11.41	956.84	408.68

Figure48: mean CoP (mm) for X and Y axes, and total swing. SD=standard deviation. No-pain, n=3; pain, n=3.

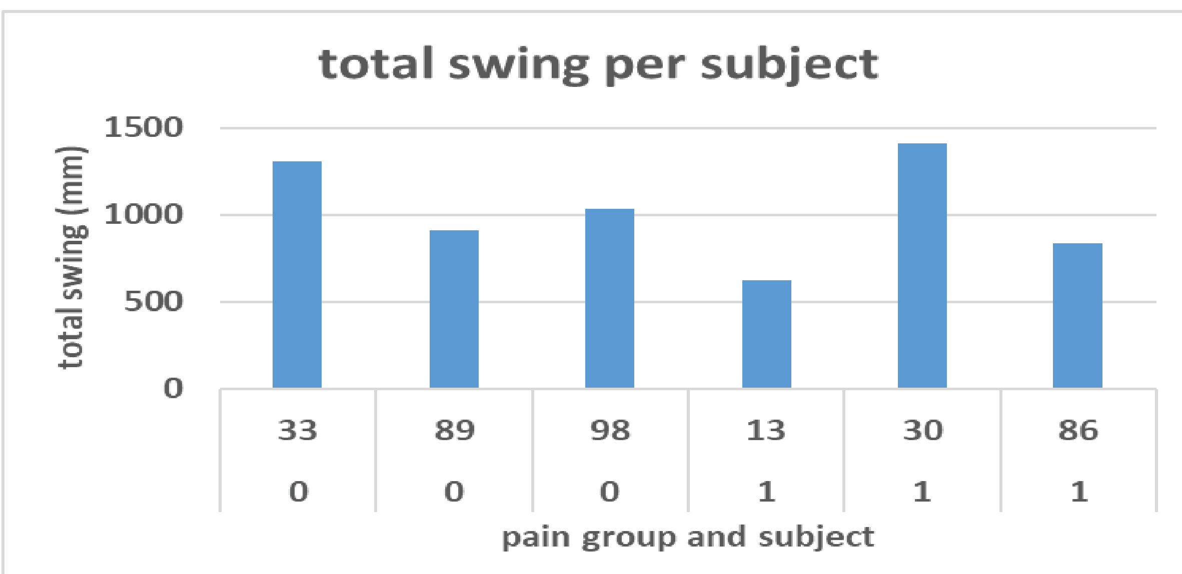


Figure 49: total swing (mm) per participant - values normalized to 10 second trial equivalent.

0=no-pain group, n=3; 1=pain group, n=3.

Calculation of body swing is intended to quantify the total amount of CoP change during the etude performance. It is not specific to particular axis orientation, and includes total position change. This involves summing the magnitude of 2-dimensional position changes between consecutive frames. Due to slight variance in the length of etude performance between participants, the numbers were averaged for a 10 second etude length for easier comparison. Clearly there is high inter-subject variability in the degree of swing demonstrated (per Figure 49). The pain group however includes participants demonstrating both the lowest and highest swing volume, possibly with a somewhat lower mean compared to the no-pain group. Given the high standard deviations for swing data, little can be concluded here.

With this small population, it does appear that total swing magnitude is doubtful as a factor in pain, though the overall orientation of CoP dominance (more rightward), may be a factor.

DISCUSSION

Some areas studied showed minimal inter-participant variability and are therefore of doubtful significance for further study as risk factors for pain. This would include left elbow, and posterior deltoid. Trombonists and teachers are familiar from personal experience and observation of colleagues, with multiple potential postural and instrument holding variations; these include truncal angulation, neck angulation, shoulder elevation, shoulder abduction, instrument angle (relative to the floor), and instrument rotation angle (around the longitudinal axis). It is reasonable to assume that the distance from the mouthpiece (embouchure) to the left-hand grip on the instrument, would pre-determine the degree of left shoulder and elbow flexion, leaving minimal inter-participant variability in these parameters. Individual tendency in how to grasp the instrument would however, offer large potential for inter-participant variation in the various wrist angles and shoulder abduction. The motion capture and EMG data supported this observation.

Predictably, GFR and CoP data demonstrated clear balance shifts relating to slide extension motion. Notable here, was the inter-participant variability in baseline direction of force and axis, laterality dominance, and unclear relationship to pain history. Whether these postural variations are primary and related to learned or inherent subject tendencies, or are secondary to some other biomechanical factor involved in playing trombone is an unanswered question.

Biomechanical parameter	Areas showing Inter-subject variability	Areas showing Pain/no-pain group variability	Significance
Joint angle motion-capture	All wrist, neck XA, all shoulder	Wrist YA, ZA, neck YA, shoulder XA	Lateral neck flexion and shoulder abduction positioning
EMG	Extensor carpi, ant deltoid, trapezius	Extensor carpi, ant deltoid, trapezius	Trapezius and shoulder abductor static load
GRF	X and Y axis	X axis	More posterior force associated with pain
CoP	Y axis	Y axis	More rightward CoP associated with pain; unclear significance of total swing volume

Figure 50: biomechanical parameter comparison

No single biomechanical modality in isolation or deviation from population “norm” studied indicated a reliable correlation with pain history. Due to the primarily static nature of LUE activity, one might conclude that motion capture study would be of limited utility, however, the degree of inter-subject variability and suggested pain group differentiation for wrist, neck and shoulder raises potential that angles adopted by the participant do influence the degree of static load, which is assumed to be a pain determinant.

It would be helpful if there existed direct parallels between the joint angles studied by motion capture, and the matching muscle group static load measured by EMG. Muscles potentially monitored by EMG often produce motion in more than one plane, and for any specific joint motion, there would typically be more than one muscle having potential involvement. The technological limitations of surface EMG recordings to standardized large muscles, and potential inaccuracies in %MVC comparisons between muscle groups and participants may limit the reliability of data trends. Potential improved accuracy with intra-muscular wire leads as an alternative to surface electrodes, particularly for smaller muscle bodies (especially wrist) may warrant consideration for further studies. The additional technological complexity of including a larger number of muscle groups in EMG data recording would however likely make the simultaneous recording of motion-capture, GRF and CoP data impractical. Despite limitations, the current study does indicate variability between subjects and between pain groups in static activity of extensor carpi, trapezius and anterior deltoid, which matches the motion-capture conclusion of degree of shoulder abduction as a factor, and suggests shoulder elevator activity as an additional determinant. Both data types suggest variable wrist positioning, and resulting static load as areas of high variability, and potential pain contributors. EMG data for wrist abduction-adduction and pronation-supination could be highly valuable here.

In further evaluation of biomechanical factors in the trombonist population, these current results would indicate that maintaining some key selected components from each of motion capture, EMG and GRF, is desirable, the complete exclusion of any of these areas likely to provide an incomplete picture. Motion capture technology combined with the GRF provides the dynamic baseline recording CoP shifts with varying slide positions and joint angles of both upper extremities, while the EMG reflects the resulting degree of static muscle load in the upper extremity.

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CHAPTER 6: CONCLUSIONS

The current literature is non-robust regarding biomechanical factor significance in trombonists experiencing pain. This study established the value of pre-existing subject models and proposed a new instrument model for the Vicon Nexus motion-capture study of trombone-playing. It further established the utility of simultaneously collected data from EMG of the LUE and Kistler-plate GRF producing CoP data, while establishing preferred camera-placement and bell-covering process to manage infrared reflections from a metallic instrument surface. Process to measure slide extension during etude performance was established.

The model and data support the assumed postural variability in holding and playing the instrument, with inter-subject and inter-pain grouping variability suggesting potential substrate for pain risk assessment. No single data type alone captured the variability adequately – the findings suggest that in future studies, it will be appropriate to maintain some key elements from each of motion-capture, EMG and GRF/CoP modalities, with more stream-lined and efficient processes to avoid potentially excessive data collection in segments with known minimal biomechanical variability and therefore presumed minimal measurement value.

A significant technological burden in data collection was lost marker data for motion capture. Missing data from a body segment later deemed minimally relevant to a trial still results in Vicon Nexus rejection for model output for that frame – Vicon process for data "repair" based on extrapolation from frames before and after, or from adjacent markers, is not always sufficient to save a trial. Development of a more-limited specific trombone and human model with substantially fewer than 39 + 6 markers, addressing only areas of importance to later study, could streamline the workload, and reduce the risk of unusable data created by transiently "unseen" but irrelevant markers. For the seated subject, motion-capture data for the lower extremities, necessary for the pre-existing conventional subject models utilized in this trial, contributes little to the biomechanical understanding, and could potentially be reasonably omitted under a simplified subject model focusing on core, and LUE only.

Other areas from the current trial, demonstrating limited learning, have potential to be excluded in future study; these include varying playing conditions and relationship of the measure to slide extension. A larger number of participants, seated, with similar repertoire, not controlling for articulation, but with pre-determined allowance for or against valve use, would be valid and of value. Elimination of elbow recording, but continued inclusion of all three axes for each of neck, left shoulder and left wrist would be anticipated to provide good quality biomechanical norms of relevance.

For EMG, posterior deltoid monitoring was of limited benefit. Inclusion of trapezius, anterior deltoid and extensor carpi in future study would be appropriate. Exploration for potential EMG monitoring of muscle activity involved in wrist Y and Z axes could allow for a richer body of data, though would likely require fine-wire intramuscular electrodes, rather than the simpler surface electrodes, for accurate measurement.

GRF and CoP output data suggest potential areas of inter-subject variability worthy of further larger group study. Thus far, the contribution of total swing data appears limited.