journal of piano research

Journal of Piano Research
© The Author(s) 2026.
This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.
https://doi.org/10.70760/GBOH9915
journalofpianoresearch.org

Antagonistic muscular co-contraction (AMCC) in piano pedagogy: An assessment of accuracy, consistency, insight, and terminology

Cobi Ashkenazi
Royal College of Music, London, UK

Aaron Williamon
Royal College of Music, London, UK

George Waddell
Royal College of Music, London, UK

Abstract

This systematic and critical content analysis assessed and consolidated piano pedagogy on the topic of antagonistic muscular co-contraction (AMCC). A central contributor to skilled movement, AMCC nevertheless remains an enigmatic and controversial topic among pianists. We identified 81 English-language pedagogical works written between 1597-2020 discussing AMCC, from which we excerpted 1,027 potentially relevant passages. We assessed each passage for clarity of terminological usage, relevance, and (dis)agreement with Ashkenazi et al.'s (2025) prior empirically-based model of AMCC. Pedagogues' discussions of AMCC were frequently inaccurate, inconsistent, and at times dangerous. We observed no significant improvement, and some significant decreases, in quality of pedagogical discussion over time. Still, pedagogues arrived at key pianistic insights about AMCC that to now have been largely absent in published science. Despite clear weaknesses in the genre, pedagogical inquiry about AMCC is therefore indispensable because of its unique contributions to understanding AMCC's nature and effects on the exceptional challenges of piano playing. This study establishes a comprehensive, critical perspective of piano pedagogy on AMCC, bridging Ashkenazi et al.'s (2025) prior model with practitioner-led discovery.

Keywords

antagonistic muscular co-contraction (AMCC), biomechanics, muscle tension, pedagogy, piano

1 Introduction

Performers and teachers have written about keyboard technique for over 400 years, generating discourse on a deceptively simple question: how can (and how should) one play the piano? This discourse includes prolonged debate about the muscle dynamics underlying skilled piano playing, particularly regarding antagonistic muscular co-contraction (AMCC), which refers to the simultaneous activation of bidirectionally paired muscles (Saliba, 2019). Co-contraction of the biceps and triceps brachii is an indicative example of AMCC: at the elbow joint, biceps contractions flex the forearm and triceps contractions extend the forearm (De Luca & Mambrito, 1987). Any simultaneous activity of both muscles therefore constitutes AMCC, which can vary in symmetry (Sun et al., 2016), intensity (Pincivero et al., 2019), temporality (Furuya & Kinoshita, 2008), appearance (Huber et al., 2017), and sensation (Latash, 2023). AMCC is a fundamental characteristic of human movement with a dualistic potential for positive and negative effects (Ashkenazi et al., 2025). In piano playing, AMCC similarly appears to be a central contributor to technical skill and health (Wheatley-Brown, 2011), both of which are of elementary importance to pianists (Goebl, 2017; Stanhope et al., 2020) and of the institutions that train them (Waddell et al., 2025).

Despite AMCC's significance, it remains unanswered precisely how this muscle activity should be integrated in the holistic context of piano playing and how pianists might best learn to do so. Pedagogical inquiry has not been able to answer these questions firmly, in part due to its endemic inconsistency and scientific inaccuracy regarding AMCC (Wheatley-Brown, 2011). Scientific research exhibits its own weaknesses, remaining largely fragmented, disconnected from expert practice, and therefore unable to reconcile fully AMCC's positive and negative effects, particularly in the context of artistic performance.

Given the significant challenges that pianists face (Kinoshita et al., 2007; Silva et al., 2015), there is a present need for a methodological approach capable of resolving the divides present among theory and practice about AMCC. This study ties together the perspectives of scientists and practitioners in a reciprocal analytical process, vetting pedagogical discussion through a quantitative lens of Ashkenazi et al.'s (2025) scientific model of AMCC, and simultaneously employing these discussions qualitatively to extend scientific insight into practicable knowledge. Our prior model concluded that AMCC is prevalent, complex, and a key facilitator of human movement, exhibiting a dualistic capacity for both positive and negative effects on performance and health. These effects appear highly relevant to the task-specific challenges of skilled, healthy piano playing: in brief, AMCC can affect sensorimotor task control, accuracy, efficiency, coordination, internal model generation, proprioception, range of motion (ROM; see, e.g., Reese & Bandy, 2017), individuation (see, e.g., Schieber, 1995), neuromuscular signal-to-noise ratio (SNR), speed, power, stability, task-related injury, pain, and rehabilitation. Our model thereby functions here both as a standard for evaluation but also as a foundation for expansion, consequently achieving an integration of theoretical and practical perspectives about AMCC's nature and effects on piano performance. While we expect to find significant inaccuracy and inconsistency in pedagogical discourse (Wheatley-Brown, 2011), we also highlight the likelihood of pedagogues making valuable, novel observations about AMCC in piano playing that have been largely overlooked by scientific inquiry.

2 Methods

2.1 Materials, search process, and inclusion criteria

Works were collected from the Royal College of Music library, the British Library, the public domain, and Cobi Ashkenazi's personal collection (primarily sourced from online booksellers). All English-language pedagogical publications (including translations) containing discussion of piano technique and muscle use were eligible for inclusion. Initial searches with terms "Piano" and "Technique" returned 925 and 325 results respectively, of which 124 were selected for potential inclusion. From the personal collection, 44 further works were identified, totaling 168.

Of these 168 works, 34 could not be retrieved (see Appendix D for a list of the works). Cobi Ashkenazi read the remaining 134 works fully, excluding 53 containing no relevant discussion of muscle use. Eighty-one works were therefore included for analysis (see Appendix C). All passages containing discussion of muscle use were excerpted into a spreadsheet and labeled. For example, the third excerpt from Fraser (2011) is labeled Fras11_03. See Supplementary Materials for the complete labeled dataset and its accompanying analytical categorizations (described below). No Artificial Intelligence tools were used in this analysis or in the preparation of this manuscript.

2.2 Excerpts for analysis

From the 81 included works, 1,027 quotations were excerpted, ranging from single sentences to multi-page discussions. These excerpts totaled 58,303 words, with a mean length of 56.8 words. More than 120 individuals are represented in this corpus. This group of commentators on muscle use in piano playing includes pedagogues of varying historical repute, as well as eminent composers and pianists such as Ludwig van Beethoven, Sergei Rachmaninoff, Claude Debussy, Frédéric Chopin, Franz Liszt, Camille Saint-Saëns, Vladimir Horowitz, and Glenn Gould. Therefore, the dataset represents not only the pedagogical state-of-the-art regarding muscle use in piano playing, but also the opinions of individuals commonly considered to be among the greatest contributors to pianism. See the Appendices and the Supplementary Materials for a list of all works, contributors, and number of excerpts per work.

2.3 Analysis

This study applies a systematic, critical content analysis to the included works and excerpts. This hybrid approach is especially valuable given the theory-practice gaps hindering understanding of AMCC in piano playing because it provides both breadth and depth via its multi-strategy analysis.

2.3.1 Terminological assessment

Before comparing pedagogical excerpts to Ashkenazi et al.'s (2025) scientific model, it was necessary to assess whether and how each excerpt defined its terminology. Pedagogues are often inconsistent in their use of terms relating to muscle use, even within a single work (Wheatley-Brown, 2011). Additionally, this polysemous terminology has varied and evolved across eras, locales, and languages. Therefore, careful terminological assessment was required to judge more conclusively and accurately whether excerpts verifiably related to AMCC, did not relate, or simply used unclear terms.

From the dataset, key terms emerged whose scientific and/or standard usages underpin and/or imply AMCC in motor contexts. See Appendix A for the definitions determined for each key term in the context of AMCC and piano playing.

Each occurrence of each key term was subcategorized into one of three epistemic groups: clear and scientific/standard usages, clear and unscientific/nonstandard usages, and unclear usages. Pedagogical claims made on the basis of clear term usage could subsequently be compared to Ashkenazi et al.'s (2025) scientific model of AMCC.

For example, Stein05_32 makes clear, scientific use of "stiffening" by relating it to AMCC and its accompanying interjoint transference of forces, therefore qualifying for assessment against Ashkenazi et al.'s (2025) prior model of AMCC. A contrasting example is Lass01_01, which asserts that "all your joints—wrist, elbows and shoulders—should be…relaxed." This passage might relate to AMCC because it contains the word "relaxed," but the scientific definition of relaxation is precluded because Lasserson is advising pianists who experience neck pain *while playing;* playing the piano requires muscle activity and active movement. However, Lasserson does not clarify her intended meaning of "relaxed" further, leaving it undefined. Therefore, the excerpt is categorized as an unclear usage of "relaxation," remaining unqualified for assessment relating to the prior model of AMCC.

2.3.2 Assessment of model agreement

Each excerpt that was verifiably relevant with Ashkenazi et al.'s (2025) prior model of AMCC was assessed on its level of agreement with this model. Either an excerpt justifiably agreed, justifiably disagreed, unjustifiably agreed, or unjustifiably disagreed with the relevant area(s) of this model. Justified agreement occurred whenever an author made a defensible, reasoned statement in agreement with the prior model. No cases of justified disagreement were observed in this study. Unjustified agreement occurred whenever an author made a statement that agreed with the prior model but did so without elaboration or arbitrarily. Finally, unjustified disagreement occurred whenever an author made a statement that disagreed with the prior model and did so indefensibly or arbitrarily. These distinctions of justification reveal the extent to which pedagogues genuinely and accurately engaged with ideas about AMCC, rather than merely asserting unsubstantiated positions.

For example, Ger07_49 justifiably agrees with Ashkenazi et al.'s (2025) finding of AMCC's benefits for efficiency by observing that "expert functioning of the various pairs of antagonistic muscles…[causes] levers [to] move with maximum efficiency."

An unjustified agreement is exemplified by Wins98_02, which implies that AMCC causes *all* upper limb pain in cellists: the excerpt agrees with the model's finding of AMCC's negative health effects but exaggerates these effects unjustifiably.

Bow61_01 represents an unjustified disagreement with the model's finding of AMCC's prevalence by incorrectly claiming that "tension in the opposite set of muscles…causes a tug-of-war…and should never be allowed if possible."

In some subcategories, assessment of level of agreement was unnecessary because discourse did not prove controversial. For example, excerpts qualifying for the subheading "Newton's third law" (a new addition to the model) did not make cases for or against this law, instead simply restating the law as an assumption of fact.

3 Results

Across the 1,027 included excerpts, 1,538 total instances of relevant discussion occurred: an *instance* refers to a unit of discussion within a single excerpt, pertaining to one or more topics relevant to Ashkenazi et al.'s (2025) model. As some excerpts contained multiple instances of discussion, and/or instances that individually pertained to more than one relevant topic, it was necessary in some cases to make calculations according to instances rather than excerpts. While this study is model-centric and primarily qualitative, quantitative analyses were also conducted to aid interpretation, context, sense-checking, and validity.

As the complete analytical commentary is > 40,000 words (excluding repeated comments), demonstrative commentary is presented here in a significantly abridged form. Readers interested in the complete analysis and commentary, particular excerpts or works, or particular areas of the scientific model of AMCC should consult the Supplementary Materials, which contain a spreadsheet of all excerpts accompanied by their corresponding categorization(s) and full commentary organized chronologically and work-by-work. The Supplementary Materials also include a text document of the full commentary, without verbatim excerpts and instead organized according to the structure of Ashkenazi et al.'s (2025) scientific model of AMCC. Alternatively, simply reading the main results here will give a broad summary of the findings. Therefore, readers are able to choose their preferred approach of engaging with our findings.

3.1 Assessment of terminology, concepts, etc.

Table 1 summarizes all assessments of key terms and relevant concepts in the dataset. Blank cells appear in categories where pedagogical logic was determined to be the analytical focus, rather than clarity.

Table 1
Summary of assessed key terms and concepts

	Total mentions (approx.)	Clear scientific/standard usage		Clear unscientific/non standard usage		Unclear usage	
Relaxation	290	71	(24.5%)	14	(4.8%)	205	(70.7%)
Tension	210	14	(6.7%)	34	(16.2%)	162	(77.1%)
Fixation	135	19	(14.1%)	44	(32.6%)	72	(53.3%)
Stiffness	97	31	(32.0%)	7	(7.2%)	59	(60.8%)
Rigidity	53	20	(37.7%)	4	(7.5%)	29	(54.7%)
Elasticity	38	6	(15.8%)	1	(2.6%)	31	(81.6%)
Contraction	37	19	(51.4%)	0	(0.0%)	18	(48.6%)
Suppleness	17	4	(23.5%)	1	(5.9%)	12	(70.6%)
Resilience	11	3	(27.3%)	0	(0.0%)	8	(72.7%)
Vibrato	8	4	(50.0%)	0	(0.0%)	4	(50.0%)
Definitions, claims, assumptions	36						
Examples, diagrams, models	8						
Muscle tone	15						
Reciprocal inhibition	2						
Implicit AMCC	32						
Column total	989	191	(21.3%)	105	(11.7%)	600	(70.0%)

Note. Miscellaneous terms were not counted due to their heterogeneity. See Appendix A for definitions of key pedagogical terms.

The most common categorization was *unclear definition of key terms*, which was therefore also the most common weakness observed in pedagogical discussion of AMCC here. Relaxation and tension were the two most commonly occurring key terms in the dataset (290 and 210 mentions, respectively). Contraction was the term used most scientifically (51.4% of usages were scientific); the term itself has a scientific connotation and therefore is comparatively unlikely to be used in an unclear and/or unscientific manner. Tension was the term used the least scientifically (6.7% of usages were scientific); this is unsurprising given the common, unscientific, pedagogical use of “tension” to mean AMCC. Elasticity was the term used the least clearly (81.6% of usages were unclear); this is not surprising given that it has a particularly complex scientific definition and no common unscientific definitions. Vibrato was the least-commonly occurring term; this seems to be because the term’s usage in the context of muscle use is an idiosyncratic coinage by Otto Ortmann (1929) that was noticed and extended by a select few

scientifically minded authors (e.g., Arnold Schultz and Thomas Fielden). However, the term describes a pattern of muscle use that is common in piano performance and is referred to via other terminology frequently.

3.2 Prior model agreement

Table 2 summarizes qualifying excerpts' instances of agreement and disagreement for each category of the model.

Table 2

Summary of pedagogical agreement with scientific model

	Total instances	(Justified) agreement		Justified disagreement	Unjustified agreement		(Unjustified) disagreement	
Prevalence	107	9	(8.4%)	0	4	(3.7%)	94	(87.9%)
Trainability	22	14	(63.6%)	0	1	(4.5%)	7	(31.8%)
Variability	32	31	(96.9%)	0	0	(0.0%)	1	(3.1%)
Limitations	6	6	(100%)	0	0	(0.0%)	0	(0.0%)
Positive effects	178	114	(64.0%)	0	15	(8.4%)	49	(27.5%)
Negative effects	30	20	(66.7%)	0	6	(20.0%)	4	(13.3%)
New additions	174	130	(74.7%)	0	9	(5.2%)	35	(20.1%)
Column total	549 (+32 implicit)	324	(55.8%)	0	35	(6.0%)	190	(32.7%)

Across the 581 qualifying instances of agreement and disagreement with the model (including those in novel categories), 0 justified disagreements were identified, suggesting that Ashkenazi et al.'s (2025) model is resilient to practical dissent. Of these 581 instances, 324 (55.8%) (justifiably) agreed with this model, while 35 (6.0%) unjustifiably agreed. Of the remaining instances, 190 (32.7%) (unjustifiably) disagreed with this model.

Fifteen works contained ≥ 10 instances of discussion verifiably related to AMCC and therefore were considered to have substantial relevant content, while 66 works contained < 10 such instances.

Across substantially relevant works, the mean level of agreement with the model was 55.3%, while insubstantially relevant works had a mean agreement level of 65.5%. There were no substantially relevant works that fully agreed with the model. Among insubstantial works, 22 had qualifying excerpts that entirely agreed with the model.

A correlation matrix was performed to compare the following variables across works: year of publication; % of model agreement; presence of self-contradiction and/or other relevant errors; size/page length of work; quantity of qualified instances; percentage of instances using clear terms; and extent of novel contributions. A Shapiro-Wilk

multivariate normality test was significant (W = .848, p < .001), so nonparametric coefficients were calculated.

There was a significant relationship between year of publication and percentage of qualifying excerpts agreeing with the prior scientific model of AMCC (τ_b = .302, p = .003, Fisher's z = .311). However, after weighting each work's percentage of excerpts agreeing with the model against the work's total quantity of qualifying excerpts, the relationship became insignificant (τ_b = -.074, p = .445, Fisher's z = -.074). This suggests that there is a significant trend of greater model agreement over time, but also that this trend is partly due to later works having fewer qualifying excerpts, and therefore being less likely to venture into increasingly complex and challenging discussions of AMCC (which are more likely to stray into disagreement on the basis of the complexity and difficulty of achieving deeper, sustained insight).

There was a significant negative relationship between a work's percentage of qualifying excerpts agreeing with the prior model and whether the work was self-contradictory (τ_b = -.253, p = .036, Fisher's z = -.258). This suggests that self-contradictory works agreed less with the model than works that were not self-contradictory. (Contradictory excerpts themselves were not penalized, nor removed.)

There was a significant negative relationship between a work's percentage of qualifying excerpts agreeing with the prior model and whether the work contained other relevant errors (τ_b = -.283, p = .020, Fisher's z = -.291). When each work's percentage of qualifying, agreeing excerpts was weighted by the work's overall quantity of qualifying excerpts, the relationship became non-significant (τ_b = .200, p = .090, Fisher's z = .203). This suggests that the dataset is skewed toward short works with errors and disagreement, as here the added weighting rewards longer, content-dense works—which, in this dataset, generally contain errors due to their length, but vary in level of agreement.

3.3 Self-contradiction and other errors

Overall, 43.2% of works were found to be meaningfully self-contradictory and 58.0% were found to contain other relevant errors. Among substantially relevant works, 100% contained both self-contradictory statements about AMCC and other relevant errors. Among insubstantially relevant works, 30.3% contained self-contradictions, 47.0% contained other errors, 24.2% contained both, and 45.5% contained neither. This suggests that, without sufficient scientific grounding, it is prohibitively difficult to engage in prolonged pedagogical discussion of AMCC without eventually falling astray of scientific consensus.

Self-contradiction appears, for example, in Ortmann (1929), which claims both that "in normal condition every muscle exerts a constant…simultaneous pull on both sides" (p. 15) and also that "most movements…involv[e]…opposite muscle-groups, one of which contracted while the other relaxed" (p. 57), implying contradictorily that a single muscle is both contracted and relaxed at the same time in normal conditions.

Other relevant errors occurred, for example, in Deahl and Wristen (2017), which misstates functional anatomy by claiming that "if both the biceps…and the triceps…are activated to the same degree…the upper arm cannot move" (p. 29). In fact, the biceps and triceps principally control the forearm in the elbow joint, exercising comparatively little control over the upper arm, unless in the unusual case of the forearm being immobilized (e.g., if a small child sits on an adult's forearm). Moreover, even if the biceps and triceps are "activated to the same degree," constituting isometric AMCC, the forearm too can

indeed still move, depending upon the relevant external forces (e.g., gravitational forces, perturbational forces from a handshake, etc.)

There were no significant relationships between a work's year of publication and whether it was self-contradictory (τ_b = -.169, p = .068, Fisher's z = -.170), or contained other errors (τ_b = -.086, p = .353, Fisher's z = -.086). This suggests that pedagogues have not changed significantly over time in their susceptibility to self-contradiction, inconsistency, and other errors when discussing AMCC.

There was a significant and strong relationship between whether a work was self-contradictory and whether it contained other relevant errors (τ_b = .585, p < .001, Fisher's z = .671). This suggests that works containing self-contradiction about AMCC were more likely to contain other relevant errors.

3.4 Individual works

Table 3 summarizes findings per-work, denoting the extent to which key terms were used unclearly, the extent to which qualifying excerpts (if any) agreed with the model, and the presence of inconsistent and/or self-contradictory content. Eight works were found to have a substantial quantity of qualifying agreement with the model (≥ 10 instances of qualifying agreement). Of these eight works, all exhibited both self-contradiction and other significant, relevant errors. Of the same eight, none entirely agreed with the model; level of agreement ranged from 50.0% to 93.1%.

Table 3
Summarized per-work findings

Author(s)	Year	Unclear key terms (approx.)	Disagreements (incl. UA)	% Agreement	Agreements (incl. implicit)	Inconsistent / contradictory	Other errors
Diruta	1597	3 (100%)	0	N/A	0		
Mitchell	1787	4 (100%)	0	N/A	0		
Schenker	ca. 1900	3 (60.0%)	0	N/A	0		
Caland*	1903	13 (92.9%)	3	72.7%	8	√	√
Steinhausen*	1905	33 (73.3%)	10	61.5%	16	√	√
Matthay*	1908	2 (40.0%)	9	10%	1	√	√
Matthay	1911	1 (50.0%)	1	0%	0		
Cooke	1913	8 (100%)	0	100%	1		√
Matthay*	1914	0 (0.0%)	33	15.4%	6	√	√
Hofmann	1920	5 (100%)	0	100%	2		
Ortmann	1925	0 (0.0%)	0	N/A	0		
Cortot	1928	5 (100%)	1	0%	0		√
Ortmann*	1929	13 (27.7%)	37	37.3%	22	√	√
Matthay*	1932	4 (23.5%)	15	6.2%	1	√	√
Fielden*	1934	26 (56.5%)	3	84.2%	16	√	√
Schmitz*	1935	2 (15.4%)	9	18.2%	2	√	√
Schultz*	1936	2 (7.4%)	15	68.1%	32	√	√
Ching*	1946	4 (18.2%)	25	80.5%	103	√	√
Coviello	1948	0 (0.0%)	1	0%	0		
Bonpensiere	1953	2 (66.7%)	2	77.8%	7		√
Harrison	1953	0 (0.0%)	2	50.0%	2		
Bolton	1954	0 (0.0%)	1	0%	0		√
Ching	1956	0 (0.0%)	3	62.5%	5	√	
Bowen	1961	1 (11.1%)	4	55.6%	5	√	√
Whiteside	1961	0 (0.0%)	1	0%	0		
Bacon	1963	8 (80.0%)	0	100%	2	√	√
D'Abreu	1964	7 (87.5%)	2	0%	0	√	√
Gat*	1965	18 (60.0%)	2	92.3%	24	√	√
Kochevitsky	1967	7 (70.0%)	2	50.0%	2	√	√
Bruxner	1972	1 (50.0%)	0	N/A	0		
Gieseking and Leimer	1972	23 (95.8%)	0	N/A	0	√	

Author(s)	Year	Unclear key terms (approx.)	Disagreements (incl. UA)	% Agreement	Agreements (incl. implicit)	Inconsistent / contradictory	Other errors
Lhévinne	1972	2 (40.0%)	0	N/A	0		√
Wolff	1972	3 (100%)	0	N/A	0		
Neuhaus	1973	9 (100%)	0	100%	3	√	
Kentner	1976	4 (44.4%)	0	100%	2	√	√
Taylor	1979	7 (77.8%)	0	N/A	0		√
Hargrave	1980	23 (100%)	0	N/A	0	√	√
Last	1980	4 (66.7%)	1	0%	0	√	√
Bernstein	1981	19 (82.6%)	0	100%	4	√	√
Sándor	1981	4 (44.4%)	7	0%	0	√	√
Taylor	1981	7 (77.8%)	1	75.0%	3	√	√
Elder	1982	16 (100%)	0	N/A	0		√
Philipp	1982	2 (100%)	0	N/A	0		
Schick	1982	4 (100%)	0	N/A	0		
Waterman	1983	4 (100%)	0	N/A	0		
Newman	1984	4 (80.0%)	0	100%	2		√
Eigeldinger	1986	4 (66.6%)	0	N/A	0		
Nicholas	1989	1 (100%)	0	N/A	0		
Fink	1992	35 (97.2%)	0	100%	5	√	√
Dubal	1993a	2 (100%)	0	N/A	0		
Manshardt	1994	5 (100%)	0	100%	2		
Lister-Sink	1995	3 (100%)	0	N/A	0		√
Sherman	1996	1 (50.0%)	0	100%	3		
Bruser	1997	22 (95.7%)	4	0%	0	√	√
Ostwald	1997	2 (100%)	0	N/A	0		
Winspur and Parry	1998	8 (50.0%)	3	0%	0	√	√
Conable	2000	4 (80.0%)	0	100%	1		
Tubiana and Amadio	2000	2 (40.0%)	0	100%	6	√	√
Grindea	2001	33 (100%)	0	N/A	0	√	√
Lasserson	2001	4 (100%)	0	N/A	0		
Kay et al.	2003	3 (75.0%)	0	100%	3		√
Mark*	2004	25 (56.8%)	5	61.5%	8	√	√
Taubman et al.	2005	1 (20.0%)	5	0%	0	√	√

Author(s)	Year	Unclear key terms (approx.)	Disagreements (incl. UA)	% Agreement	Agreements (incl. implicit)	Inconsistent / contradictory	Other errors
Walker	2005	0 (0.0%)	0	100%	1		
Altenmüller et al.	2006	0 (0.0%)	0	100%	1		
Soderlund	2006	4 (100%)	0	N/A	0		
Barnes	2007	2 (50.0%)	3	50%	3		√
Gerig*	2007	28 (47.5%)	4	81.8%	18	√	√
Grindea	2007	21 (100%)	0	100%	1		√
Knudson	2007	0 (0.0%)	0	100%	1		
Walker	2010	2 (100%)	0	N/A	0		
Fraser*	2011	103 (85.1%)	7	70.8%	17	√	√
Abernethy	2013	1 (100%)	0	N/A	0		√
Wallick	2013	3 (100%)	0	100%	1		√
Karpeyev	2014	1 (100%)	0	N/A	0		
Roberts	2014	5 (100%)	0	100%	2		
Stannard	2014	2 (100%)	0	N/A	0		√
Deahl and Wristen*	2017	6 (75.0%)	4	69.2%	9	√	√
Lister-Sink	2018	1 (100%)	0	100%	1		
Doran	2020	0 (0.0%)	0	100%	1		
Koumis	2020	3 (30.0%)	0	100%	1	√	√
Column means		70.0%	2.8 disagreements / work	63.2% level of agreement	4.4 agreements / work	43.2% were self-contradictory	58.0%

Note. Works containing substantial discussion of AMCC are marked with an asterisk (*).

3.5 Assessment of model findings: Characteristics of AMCC

Table 2 summarizes the analyzed excerpts pertaining to AMCC's characteristics as determined by Ashkenazi et al. (2025). Of the 581 total instances of verified discussion of AMCC, 167 (28.7%) related to AMCC's characteristics. Of these 167, 60 (35.9%) were justified agreements, 5 (3.0%) were unjustified agreements, and 102 (61.1%) were unjustified disagreements. Specifically, most of these 167 instances were unjustified disagreements with AMCC's prevalence and ubiquity (94 unjustified disagreements; 56.3%). There was no verified discussion of AMCC's individual variability, gender variability, nor age variability.

3.6 Assessment of model findings: Positive effects of AMCC

Table 4 summarizes the analyzed excerpts pertaining to AMCC's positive effects as determined by Ashkenazi et al. (2025). Of the 581 total instances of verified discussion of AMCC, 179 (30.8%) related to AMCC's positive effects. Of these 179, 115 (64.2%) were justified agreements, 15 (8.4%) were unjustified agreements, and 49 (27.4%) were

unjustified disagreements. There was no verified discussion of AMCC's positive effects on internal model generation, signal-to-noise ratio, and lower-body stability.

Table 4 also summarizes the dataset's verified discussions of AMCC's negative effects as determined by Ashkenazi et al. (2025). Of the 581 total instances of verified discussion of AMCC, 29 (5.0%) related to AMCC's negative effects. Of these 29, 20 (69.0%) were justified agreements, 5 (17.2%) were unjustified agreements, and 4 (13.8%) were unjustified disagreements. There was no verified discussion of AMCC's negative effects on efficiency, flexibility, multijoint dynamics, proprioception, signal-to-noise ratio, speed, and power.

Table 4

Summary of excerpts relating to Ashkenazi et al.'s (2025) AMCC model

	Justified agreement		Unjustified agreement		Unjustified disagreement		Total	
Sensorimotor	1	6.3%	0	0.0%	15	93.8%	16	8.9%
Accuracy/precision	14	56.0%	1	4.0%	10	40.0%	25	14.0%
Efficiency	2	50.0%	0	0.0%	2	50.0%	4	2.2%
Multijoint dynamics	32	78.0%	4	9.8%	5	12.2%	41	22.9%
Internal model	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Proprioception	0	0.0%	0	0.0%	2	100.0%	2	1.1%
Range of motion; individuation	4	57.1%	1	14.3%	2	28.6%	7	3.9%
SNR	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Speed and power	29	70.7%	4	9.8%	8	19.5%	41	22.9%
General stability	17	65.4%	5	19.2%	4	15.4%	26	14.5%
Upper stability	11	100.0%	0	0.0%	0	0.0%	11	6.1%
Lower stability	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Trunk stability	4	100.0%	0	0.0%	0	0.0%	4	2.2%
Health benefits	1	50.0%	0	0.0%	1	50.0%	2	1.1%
Total	115	64.2%	15	8.4%	49	27.4%	179	100%

Note. See Ashkenazi et al. (2025) for further information regarding each category.

3.7 New additions to the model

Instances qualifying as novel contributions to Ashkenazi et al.'s (2025) model were determined inclusively. For example, a novel contribution from a work published in 1912, and the same contribution from a work published in 2002, would both qualify as novel. Table 2 summarizes the dataset's verified instances of novel topics relating to AMCC. Of

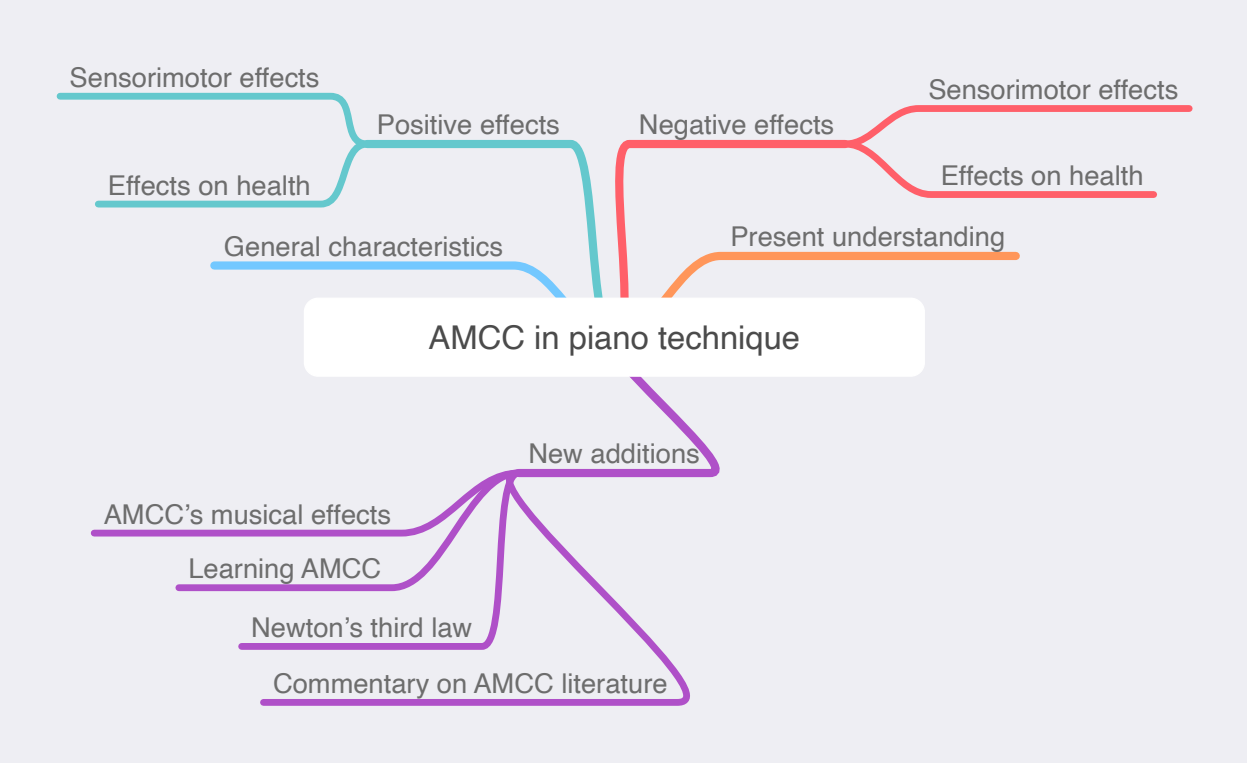
the 581 total instances of verified discussion of AMCC, 174 (30.0%) related to AMCC's characteristics as determined by Ashkenazi et al. (2025). Of these 174, most instances clustered around four categories of novel contribution: 36 (20.7%) related to the sensations of AMCC, 59 (33.9%) related to ideomotor theory, 38 (21.8%) related to multisensory effects, and 21 (12.1%) related to AMCC's musical effects. There were also minor, novel discussions of Newton's third law (7 instances), insufficient AMCC (4 instances), the importance of AMCC research (4 instances), and critiques of other pedagogical approaches to AMCC in piano playing (5 instances).

There was no significant relationship between year and number of novel contributions to the prior model (τ_b = -.078, p = .359, Fisher's z = -.078). This lack of a significant relationship (alongside our inclusive determination of novelty) suggests that modern authors were no more likely to discuss topics qualifying as novel contributions than earlier authors.

Figure 1 displays an updated model of AMCC: a simplified version of Ashkenazi et al.'s (2025) model of AMCC is reproduced in the top half of the figure, while a summary of new model additions appears in the bottom half. The Supplementary Materials include the full, unsimplified model, including all 1,538 individual instances of discussion that we verified as pertaining to AMCC.

Figure 1

Expanded model of AMCC



4 Discussion

This study has systematically critiqued piano pedagogy about antagonistic muscular co-contraction (AMCC), expanding Ashkenazi et al.'s (2025) scientific model of AMCC with the novel insights of practitioners and bridging persistent theory-practice gaps impeding

progress in understanding of skilled piano performance. Alongside Ashkenazi et al. (2025), these two studies begin to establish an epistemological integration of the present state of knowledge on AMCC in piano playing.

4.1 Weaknesses in pedagogical inquiry

None of the 81 works included in this study can be highly recommended for their discussion of AMCC. Many works' discussions of AMCC are simply brief and insubstantial, while those works containing prolonged discussion of AMCC tend toward unjustified disagreement with Ashkenazi et al.'s (2025) model of AMCC. The few substantial works that lean toward agreement with this model nevertheless still exhibit noteworthy weaknesses, making their recommendation to general readership inadvisable.

This study's systematic and critical methodology is further justified by the endemic vagueness (70.0% of key terms were used unclearly), self-contradiction (43.2% of works, including all substantially relevant works, were self-contradictory), and other errors (58.0% of works, including all substantially relevant works, contained other relevant errors) that pedagogues exhibited in discussing AMCC. Casual readers seeking advice about muscle use from the collection of over 400 years of published piano pedagogy represented in this study are at risk of misunderstanding the authors, or of adopting self-contradictory or specious advice. Readers who happen upon any of the works here that did not contain such weaknesses will still be unable to glean more than a small amount of verifiable, internally and empirically consistent information about AMCC. Furthermore, only 65.5% of this consistent information agreed with scientific consensus about AMCC, and the disagreed claims were found to be made unjustifiably. Readers of works containing substantial AMCC discussions enter problematic pedagogical territory. Even when these discussions are verified and internally consistent, they align with Ashkenazi et al.'s (2025) scientific model of AMCC an average of only 55.3% of the time.

Simply put, the extant English-language pedagogical literature regarding AMCC in piano playing appears particularly dangerous (i.e., "able or likely to cause harm or injury"; Oxford University Press, 2015, sense 1) to those most in need of the assistance this literature purports to offer: pianists struggling with technique and playing-related health who have been unable to achieve satisfactory improvement through the ports-of-call of their instructors, colleagues, and healthcare professionals.

4.1.1 Terminological concerns, self-contradictions, and other errors

In some regards, discussion of AMCC has apparently not improved over the four centuries that have elapsed since Diruta (1597). Although the newest included work (Koumis, 2020) defines terminology comparatively more clearly, it is self-contradictory regarding AMCC and contains other relevant errors; Diruta (1597), by contrast, exhibits neither of these concerns.

Qualifying instances that related to Ashkenazi et al.'s (2025) model were split somewhat evenly between agreements and disagreements. Despite this, during analysis we observed an overall trend of pedagogues typically being opposed to AMCC. This trend is particularly interesting given that these pedagogues achieved merely 20 instances of justified agreement with the model's findings of genuinely negative effects of AMCC, yet 49 instances of unjustified disagreement and 115 instances of justified agreement with the model's findings of positive effects of AMCC. This suggests that, even when managing

to use terms clearly, pedagogues were generally unable to defensibly justify their anti-AMCC positions, spending much more time futilely assailing AMCC's positive effects than making justifiable observations about its real negative effects.

4.1.2 Gaps in pedagogical awareness

Notably, pedagogues failed to address several areas of our prior model: AMCC's individual variability, gender variability, age-related variability, positive effects on internal model generation, signal-to-noise ratio (SNR), lower-limb stability, and negative effects on flexibility, inter-joint transference, speed and power output proprioception, and SNR. This list is rather small, especially given that topics like internal motor models and SNR are relatively modern concepts that were not widespread nor commonly considered during much of the period of the dataset here (nor were pianists' demographics). The absence of discussion about lower limb stability is also unsurprising given the comparative simplicity of the lower body in piano playing. Apart from these minor gaps, pedagogues successfully engaged with nearly all aspects of AMCC as described by Ashkenazi et al.'s (2025) model, though in some cases this engagement was quite sparse: for example, only two (problematic) mentions of AMCC's effects on proprioception (whether positive or negative), and only a single (problematic) mention of AMCC's negative effects on general sensorimotor function.

4.2 Strengths of pedagogical inquiry

Pedagogues did arrive at justified disagreement with an earlier, now antiquated scientific consensus: for example, Thomas Fielden in 1934 (despite numerous errors in other regards) writes presciently in support of dynamic AMCC in "all movements" (Fielden, 1934, p. 130), making accurate judgments about human motor function long before more modern biomechanical models that consistently underestimate AMCC even existed—let alone before these flawed models became obsolete (Kian et al., 2019). Nearly fifty years after Fielden (1934), AMCC was still "neglected by most investigators" in scientific research (Nissan, 1980, p. 381). This is not to say that Fielden's work should have galvanized new attention to AMCC at the time; like all substantially relevant works here, it contains significant errors, self-contradictions, vague terms, and other concerns that make proper interpretation frequently impossible (and when possible, often exceedingly difficult).

The principal achievement of these pedagogues' largely informal, practitioner-led inquiries is that they were able to contribute novel observations about AMCC in the context of piano performance, producing and convincingly communicating valuable understanding that scientific literature has scarcely explored to date. These authors' novel insights clustered mainly around four topics:

4.2.1 Sensations, awareness, and appearances of AMCC

Authors identified that achieving accurate awareness and assessment of AMCC via its sensory outputs is of key importance in learning and maintaining its proper functions in piano playing. Authors also observed that this sensory awareness and its interpretation are both especially difficult and at times misleading, implying the value of special care in the teaching and learning of a refined physical awareness of AMCC, and also providing a further explanation for why pedagogical inquiry itself has struggled significantly to achieve valid, accurate understanding of AMCC at the piano: because this inquiry (in contrast with most scientific research) is largely made on the basis of these elusive and

ambiguous sensations themselves. Research similarly suggests the importance of both interoceptive and exteroceptive function in cognition and action (Garfinkel & Eccleston, 2025).

4.2.2 Ideomotor theory

Authors dwelled at length on the proper sequencing of the mental and physical constituents of musical performance, both in relation to AMCC and more generally. Many authors expressed a pro-ideomotor perspective by asserting that the musical concept (idea) must precede and give rise to the physical phenomena responsible for its performance (motor function). Some authors took this position to doctrinaire extremes, adamantly asserting that any consideration whatsoever of the physical elements of piano performance is dangerous and counterproductive, or that skilled piano performance is developed entirely in the brain. In contrast, other authors suggested (whether intentionally or not) that all piano playing is entirely determined by the physiological mechanics of the pianist and the instrument—leaving no sliver of room for the performer's interpretational concept. Finally, a few authors instead offered perspectives that appear to reconcile these dichotomous positions by conceiving of piano performance as an interdependent, simultaneous integration of the mental and physical elements that constitute its nature. This pedagogical entwining of idea and execution echoes this study's efforts at the integration of theory and practice in research, hinting at a congruent methodological harmony between the act of researching performance and the act of performance. It thereby serves as a lens to explore a fundamental question in performance science: how the human mind and body interact during the development and maintenance of skilled performance.

4.2.3 Multisensory effects

Many authors emerged into two camps regarding multisensory effects on musical perception, a topic which is inextricably linked to the question of timbre (i.e., tone color, tone quality, etc.) and its relationship to piano and pianist. Recent research has isolated and confirmed effects of multisensory perception at the piano, finding these effects to be of considerable impact on how listeners (whether expert performers or nonmusicians) hear piano timbre, itself often considered to be the single most important element in piano playing (Ashkenazi, 2021; Bernays, 2013). Multisensory perception also affects how we hear the piano's dynamics, articulation, and other key elements of musical expression. Beyond AMCC's numerous effects on the acoustic outcomes of piano performance, AMCC also exercises considerable influence on the kinesthetic and visual perceptions of movement—both for the performer and for their audience, if any. The perceived expressive character of any note (or silence), regardless of its length, can be desirably (or undesirably) affected by these perceptions of movement, implying that a comprehensive model of AMCC's effects on piano playing must also account for its multisensory effects on perceived musical expression. In this study, while many authors predictably and wrongly asserted an absolute impossibility of timbral control, a few works did observe the expressive importance of the quality of a pianist's movements in relation to subjective, perceptual effects (as opposed to the objective, acoustic output of the piano itself). In sum, although many works repeated the debunked pedagogical assertion that timbre is strictly coupled to amplitude, authors broadly agreed on the importance of correctly assessing the factors contributing to piano timbre and of how we perceive it, and

some additionally identified AMCC as capable of affecting timbre (both positively and negatively), either attributing this capability directly to multisensory perceptual effects, or simply resigning it to an unexplained (or unexplainable) mystery.

4.2.4 Musical effects of AMCC

Beyond AMCC's effects on multisensory perception of piano timbre, authors commented varyingly on AMCC's general musical and expressive effects: often either by suggesting that AMCC is necessary and required to achieve expressive musical performance, or by adopting an opposing view, that AMCC prohibits or at minimum significantly impairs expressive musical performance. These conflicting positions are neatly reconciled via Ashkenazi et al.'s (2025) model, which found that AMCC can exhibit both positive and/or negative effects on phenomena related to piano technique. In short, AMCC with dynamic and proportionate characteristics is a necessity for expressive musical performance—but alternately, maladaptive AMCC, with static and excessive characteristics, instead has proportionally negative effects on expressive musical performance.

Beyond the key contributions listed above, pedagogues also made significant, though less substantial exploration of other relevant topics not categorized by Ashkenazi et al.'s (2025) scientific model: Newton's third law, insufficient AMCC, the importance of AMCC research, and critiques of pedagogical approaches to AMCC.

5 Limitations and future directions

The study only included English-language works and works translated into English. Additionally, only works accessible via the RCM Library and reader access at the British Library were included. Nevertheless, the amount of literature included is still substantial and appears sufficient at this time for assessment of general trends about AMCC in piano pedagogy. Future studies containing works from other languages will naturally provide broader insights.

To maintain a balanced view of the dataset and maximize analytical validity, we could not seek clarification from any authors of the included works. Similarly, interpretational guesswork was minimized. Even if a friendlier interpretation of an unclear passage was apparent, it was still interpreted strictly according to what was on the page. This makes the study somewhat less insightful about the intended meanings of the included works than might be justifiable on the basis of looser interpretations, particularly in the case of works that are held back by lack of strictly clear definitions and discussions.

But despite its strict interpretational approach, the study's analysis is nevertheless subjective to some degree. However, our positions as pianists, pedagogues, and scientists do imply that we are well-placed to interpret these works.

Due to the dataset's size, it was not feasible to excerpt every relevant sentence in the case of repetitious discussion across a work. This dampened outlier effects in number of excerpts per text, number of total excerpts, number of excerpts discussing muscle tone, etc. These statistics should be interpreted cautiously, especially given the heterogeneity and incompleteness of the dataset; readers should not rely on this study for a conclusive statistical analysis of AMCC terminology. (In contrast, all qualifying term uses were coded against Ashkenazi et al.'s (2025) model of AMCC.)

A further limitation is that many (though not all) of our judgments here are underpinned by the assumption that the research forming the basis of Ashkenazi et al.'s (2025) prior scientific model is itself accurate and representative of AMCC's veridical

nature. This scientific knowledge itself will inevitably continue to evolve, subject to further scientific progress and understanding. Therefore, these judgments of pedagogy about AMCC cannot be taken as permanently conclusive, but instead are representative of the status quo of scientific research.

6 Conclusions

This study has established novel findings about AMCC in the context of piano playing: both as an intractable 400-year-old hobbyhorse of keyboardists, and as an important contributor to pianistic skill and health. The discoveries made here of the shortcomings and strengths of pedagogical approaches to understanding AMCC, alongside those of scientific approaches to the same task, have reinforced our rationale in seeking a theory-practice integration in investigating AMCC which might be applied to other topics across the performing arts. The study has critiqued and synthesized common pedagogical weaknesses, simultaneously extracting new, relevant findings about AMCC in the context of piano playing. These additions to the model require further scientific validation, given that they are not made on the basis of a scientific consensus but rather drawn from a practitioner-led discourse that exhibits diverse and conflicting findings. In the meantime, pianists and piano educators are encouraged to use the detailed analyses accompanying this report to assess the validity of specific excerpts found in their chosen pedagogical texts and to consult a range of sources in furthering their understanding of AMCC as it relates to healthy, sustainable, and effective piano practice.

Funding Statement

Financial support was received for the research of this article. Cobi Ashkenazi's doctoral research was funded by the London Arts Humanities Partnership, part of the Arts & Humanities Research Council (UKRI Project Reference: 2616569).

Data Access Statement

The data presented in the study are included in the Supplementary Materials; further inquiries can be directed to the corresponding author.

ORCID iD

Cobi Ashkenazi https://orcid.org/0000-0002-1228-4325
Aaron Williamon https://orcid.org/0000-0002-1713-6161
George Waddell https://orcid.org/0000-0001-9715-2753

References

Al Dhuhaibwi, A. H. (2018). Opinions on the role and development of suppleness to prevent shoulder dislocation in performance athletes. Discobolul – Physical Education, Sport and Kinetotherapy Journal, XIV(3(53)), 10–16.

Ashkenazi, C. (2021). *Multisensory visual-auditory perception of piano timbre* [Unpublished Master of Science thesis, Royal College of Music].

Ashkenazi, C., Waddell, G., & Williamon, A. (2025). Antagonistic muscular co-contraction for skilled, healthy piano technique: A scoping review. *Frontiers in Psychology, 16*. https://doi.org/10.3389/fpsyg.2025.1386273

Bernays, M. (2013). *The expression and production of piano timbre: gestural control and technique, perception and verbalisation in the context of piano performance and practice*. [Doctoral dissertation, University of Montreal]. https://umontreal.scholaris.ca/items/558e9906-8507-4bf7-bd0f-f35467957f09

Crozier, C. P. (1941). *The principles of keyboard technique in Il Transilvano by Girolamo Diruta* [Master's thesis, University of Rochester]. UR Research. http://hdl.handle.net/1802/5170

De Luca, C. J., & Mambrito, B. (1987). Voluntary control of motor units in human antagonist muscles: Coactivation and reciprocal activation. *Journal of Neurophysiology, 58*(3), Article 3. https://doi.org/10.1152/jn.1987.58.3.525

Deahl, L., & Wristen, B. G. (2017). *Adaptive strategies for small-handed pianists*. Oxford University Press.

Diruta, G. (1597). *Il Transilvano: Dialogo sopra il vero modo di sonar organi, & istromenti da penna*. Giacomo Vincenti.

Farjam, P., Hekman, E. E. G., Rouwkema, J., & Verkerke, G. J. (2022). Bone fixation techniques for managing joint disorders and injuries: A review study. *Journal of the Mechanical Behavior of Biomedical Materials, 126*, 104982. https://doi.org/10.1016/j.jmbbm.2021.104982

Fielden, T. (1934). *The science of pianoforte technique*. Macmillan.

Florina, N. (2022). Contributions to the Development of Speed and Suppleness in Hurdlers. In *Proceedings of the Actualities and Perspectives of Physical Education and Sport Sciences* (pp. 143–147). https://ibn.idsi.md/sites/default/files/imag_file/Proceedings_UEB_2022_final.pdf#page=143

Fraser, A. (2011). *The craft of piano playing: A new approach to piano technique* (2nd ed.). Scarecrow Press.

Furuya, S., & Kinoshita, H. (2008). Organization of the upper limb movement for piano key-depression differs between expert pianists and novice players. *Experimental Brain Research, 185*(4), 581–593. https://doi.org/10.1007/s00221-007-1184-9

Garfinkel, S. N., & Eccleston, C. (2025). Interoception and pain: Body–mind integration, rupture, and repair. *PAIN, 166*(7), 1470. https://doi.org/10.1097/j.pain.0000000000003515

Goebl, W. (2017). Movement and touch in piano performance. In B. Müller, S. I. Wolf, G.-P. Brueggemann, Z. Deng, A. McIntosh, F. Miller, & W. S. Selbie (Eds.), *Handbook of human motion* (pp. 1–18). Springer International Publishing. https://doi.org/10.1007/978-3-319-30808-1_109-1

Gordon, J. B., Desaix, P., Johnson, E., Johnson, J. E., Korol, O., Kruse, D., Poe, B., Wise, J. A., Womble, M., & Young, K. A. (2022). *Anatomy and physiology* (2nd ed.). OpenStax, Rice University.

Huber, M. E., Folinus, C., & Hogan, N. (2017). Visual perception of limb stiffness. *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 3049–3055. https://doi.org/10.1109/IROS.2017.8206143

Kian, A., Pizzolato, C., Halaki, M., Ginn, K., Lloyd, D., Reed, D., & Ackland, D. (2019). Static optimization underestimates antagonist muscle activity at the glenohumeral joint: A musculoskeletal modeling study. *Journal of Biomechanics*, *97*, 109348. https://doi.org/10.1016/j.jbiomech.2019.109348

Kinoshita, H., Furuya, S., Aoki, T., & Altenmüller, E. (2007). Loudness control in pianists as exemplified in keystroke force measurements on different touches. *The Journal of the Acoustical Society of America, 121*(5), Article 5. https://doi.org/10.1121/1.2717493

Kobayashi, M., Takemori, S., & Yamaguchi, M. (2004). Differential rigor development in red and white muscle revealed by simultaneous measurement of tension and stiffness. *Forensic Science International, 140*(1), 79–84. https://doi.org/10.1016/j.forsciint.2003.11.026.

Koumis, M. (2020). *Mind + Body + Piano: How to play the piano effortlessly like a pro*. Patamos Music Books.

Lasserson, N. (2001). *Dr. Downing's piano technique doctor*. Downing.

Latash, M. L. (2023). The control and perception of antagonist muscle action. *Experimental Brain Research, 241*(1), 1–12. https://doi.org/10.1007/s00221-022-06498-1

McConnell, A. J., Yoo, D. J., Zdero, R., Schemitsch, E. H., & McKee, M. D. (2007). Methods of operative fixation of the acromio-clavicular joint: A biomechanical comparison. *Journal of Orthopaedic Trauma, 21*(4), 248–253. https://doi.org/10.1097/BOT.0b013e31803eb14e.

Nagai, K., Yamada, M., Mori, S., Tanaka, B., Uemura, K., Aoyama, T., Ichihashi, N., & Tsuboyama, T. (2013). Effect of the muscle coactivation during quiet standing on dynamic postural control in older adults. *Archives of Gerontology and Geriatrics, 56*(1), Article 1. https://doi.org/10.1016/j.archger.2012.08.009.

Nissan, M. (1980). Review of some basic assumptions in knee biomechanics. *Journal of Biomechanics, 13*(4), Article 4. https://doi.org/10.1016/0021-9290(80)90018-4

Ortmann, O. (1929). *The physiological mechanics of piano technique*. E.P. Dutton & Co.

Osu, R., Franklin, D. W., Kato, H., Gomi, H., Domen, K., Yoshioka, T., & Kawato, M. (2002). Short- and long-term changes in joint co-contraction associated with motor learning as revealed from surface emg. *Journal of Neurophysiology, 88*(2), 991–1004. https://doi.org/10.1152/jn.2002.88.2.991

Oxford University Press. (2015). Dangerous. In *Oxford Dictionary of English* (3rd ed.).

Patrick, S. K., Denington, A. A., Gauthier, M. J. A., Gillard, D. M., & Prochazka, A. (2001). Quantification of the UPDRS rigidity scale. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 9*(1), 31–41. https://doi.org/10.1109/7333.918274

Pincivero, D. M., Polen, R. R., & Byrd, B. N. (2019). Contraction mode and intensity effects on elbow antagonist muscle co-activation. *Journal of Electromyography and Kinesiology, 44*, 101–107. https://doi.org/10.1016/j.jelekin.2018.12.002

Reese, N. B., & Bandy, W. D. (2017). *Joint range of motion and muscle length testing*. Elsevier.

Rouse, E. J., Gregg, R. D., Hargrove, L. J., & Sensinger, J. W. (2013). The difference between stiffness and quasi-stiffness in the context of biomechanical modeling. *IEEE Transactions on Biomedical Engineering, 60*(2), 562–568. https://doi.org/10.1109/TBME.2012.2230261

Saliba, C. M. (2019). *Two muscles are better than one: Co-contraction engages antagonistic muscles in response to perturbation*. Queen's University.

Schieber, M. H. (1995). Muscular production of individuated finger movements: the roles of extrinsic finger muscles. *Journal of Neuroscience, 15*(1), 284-297. https://doi.org/10.1523/JNEUROSCI.15-01-00284.1995

Sepehri, B., Esteki, A., Ebrahimi-Takamjani, E., Shahidi, G.-A., Khamseh, F., & Moinodin, M. (2007). Quantification of rigidity in parkinson's disease. *Annals of Biomedical Engineering, 35*(12), 2196–2203. https://doi.org/10.1007/s10439-007-9379-6

Serway, R. A., & Jewett Jr, J. W. (2008). *Physics for scientists and engineers with modern physics* (7th ed.). Thomson Higher Education.

Silva, A. G., Lã, F. M., & Afreixo, V. (2015). Pain prevalence in instrumental musicians: a systematic review. *Medical Problems of Performing Artists, 30*(1), Article 1. https://doi.org/10.21091/mppa.2015.1002

Soutas-Little, R. W. (1999). *Elasticity* (unabridged reproduction of the 1st ed. 1973). Dover Publishing.

Stanev, D., & Moustakas, K. (2019). Stiffness modulation of redundant musculoskeletal systems. *Journal of Biomechanics, 85*, 101–107. https://doi.org/10.1016/j.jbiomech.2019.01.017

Stanhope, J., Weinstein, P., & Pisaniello, D. (2020). What can musicians' claims data reveal about their musculoskeletal conditions? *Archives of Environmental & Occupational Health, 75*(3), 177–190. https://doi.org/10.1080/19338244.2019.1605968

Sun, W., Liang, J., Yang, Y., Wu, Y., Yan, T., & Song, R. (2016). Investigating aging-related changes in the coordination of agonist and antagonist muscles using fuzzy entropy and mutual information. *Entropy, 18*(6), 229. https://doi.org/10.3390/e18060229

Waddell, G., Hockings, D., & Williamon, A. (2025). The healthy musician. In C. Lawson, D. Salazar, & R. Perkins (Eds.), *Inside the contemporary conservatoire: critical perspectives from the Royal College of Music, London* (pp. 156–166). Routledge.

Wallick, B. (2013). *Piano practice: Practice routines and techniques for concert pianists*. University of Pretoria.

Wheatley-Brown, M. (2011). *An analysis of terminology describing the physical aspect of piano technique*. [Master's thesis, University of Ottawa]

Appendix A

Definitions of key pedagogical terms relating to AMCC

Key term	Definition	Relevance	Reference(s)
Elasticity	The property of a material or object that "may be deformed and will return to its original configuration upon release of the deforming loads."	AMCC is the primary means of controlling joint elasticity.	Soutas-Little (1999), p. 66
Tension	A scalar quantity defined as the magnitude of a force pulling away from an object; "the force generated by the contraction of a muscle."	AMCC requires two or more simultaneous, antagonistic tensions.	Serway and Jewett (2008) Gordon et al. (2022), p. 372
Relaxation	The absence or cessation of muscle activity.	Both total and one-sided relaxation preclude AMCC.	Gordon et al. (2022)
Fixation	The action or process of fixing or being fastened [maintained] securely in position.	AMCC is the primary means of controlling joint and limb fixation during complex movement.	OED
Rigidity	A quantifiable material property, equivalent to viscoelastic stiffness and related to mechanical impedance. The more rigid a joint, the more it resists the displacement of its attached limb segments.	AMCC is the primary means of controlling joint rigidity.	Patrick et al. (2001) Stanev and Moustakas (2019)
Stiffness	Equivalent to rigidity (see above).	AMCC is the primary means of controlling joint stiffness.	Patrick et al. (2001) Stanev and Moustakas (2019)
Contraction	The act of "shorten[ing] and generating a pulling force" (Gordon et al., 2022, p. 147). Muscle contraction therefore is defined as a muscle's process of activating its fibers to (typically) exert pulling forces on bones via tendinous interconnections.	AMCC requires two or more simultaneous, antagonistic contractions.	Gordon et al. (2022), p. 147

Key term	Definition	Relevance	Reference(s)
Suppleness*	A state of elasticity and flexibility that is characterized by ease and grace.	Typically requires dynamic, adaptive AMCC.	Al Dhuhaibwi, 2018 Florina, 2022 OED
Vibrato*	The act of vibrating, moving, or swinging continuously and rapidly to and fro, backwards and forwards, or side to side; swift oscillation in a regular rhythm.	Implies unavoidable AMCC due to its alternating directions and speed.	OED
Resilience*	Equivalent to elasticity (see above).	AMCC is the primary means of controlling joint resilience.	OED

Note. Terms marked with an asterisk (*) had no common, agreed-upon scientific definition in the context of piano playing, and therefore are given newly formed 'standard' definitions here. All other terms are defined by common scientific usage.

Appendix B

Extended definitional rationales

Key term	Full rationale and definition	Relevance
Elasticity	While elasticity can broadly mean "the ability to change and adapt; adaptability" (OED), in mechanical or physical contexts it more specifically is a property that implies that a material or object "may be deformed and will return to its original configuration upon release of the deforming loads" (Soutas-Little, 1999, p. 66). This impending return to original configuration, in the context of joint movement, typically implies AMCC (Osu et al., 2002), so that preemptive (as opposed to reactive), dynamically adjusted antagonistic forces at a joint may swiftly recover the position of its corresponding limb segment after experiencing a temporary deformation (via displacement/perturbation).	AMCC is the primary means of controlling joint elasticity.
Tension	In physics, "tension" is a scalar quantity defined as the magnitude of a force pulling away from an object (Serway & Jewett, 2008). More specifically, muscle tension can be defined as "the force generated by the contraction of a muscle," which itself is a force pulling away from an object (Gordon et al., 2022, p. 372). Therefore, all muscle contraction (including AMCC) creates tension, and all active movement cannot occur	AMCC requires two or more simultaneous, antagonistic tensions.

Key term	Full rationale and definition	Relevance
	without tension. In contrast, passive movement (any movement in a joint that is caused by any force external to the immediately adjacent muscles and the tendons that cross the joint—for example, being moved by another person's actions, or, generating passive flopping movements in a relaxed wrist via undulating movements of the upper arm) can occur without local contractile tension.	
Relaxation	In biomechanical contexts, "relaxation" refers to the absence (or cessation) of muscle activity—beginning with the motor neurons, which stop releasing signals to the muscle, enacting a complex biochemical process that quickly results in the muscle fibers losing their ability to generate tension (Gordon et al., 2022). In healthy muscle tissue, contraction and relaxation alternate perpetually and temporally inconsistently—no muscle remaining permanently in a state of total relaxation nor maximal contraction. Therefore, while "relaxed" muscle implies the total absence of contraction, a "relaxing" muscle implies a muscle that is currently releasing a prior state of contraction, either partly or completely—meaning that a "relaxing" muscle is by definition not "relaxed," because a "relaxed" muscle is not in a state of contraction, and therefore cannot be made to "relax" any further. In contrast, "relaxation" can refer either to the state of being relaxed or also to the process of relaxing—which again is mutually exclusive with the state of being fully relaxed.	Both total and one-sided relaxation preclude AMCC.
Fixation	In human movement contexts, "fixation" typically refers to the practice of orthopedic implantation to improve function in joint disorders and injuries (Farjam et al., 2022); for example, the coraco-clavicular Bosworth screw, which is implanted to artificially rejoin the clavicle and coracoid process of the scapula after acute acromioclavicular joint disruption, effectively reconstructing the joint (McConnell et al., 2007). This usage has little relevance to the meaning of "fixation" in piano pedagogy, and there does not appear to be an established alternative usage (e.g., in biomechanics literature) that would be a more	AMCC is the primary means of controlling joint and limb fixation during complex movement.

Key term	Full rationale and definition	Relevance
	appropriate comparator to pedagogical fixation. Therefore, we proceed to adopt a loose standard definition of "fixation" as "the action or process of fixing or being fixed" (OED). This requires a further definition, for "fixed": "fastened [maintained] securely in position" (OED).	
Rigidity	In biomechanical contexts, rigidity can be considered a quantifiable material property, equivalent to viscoelastic stiffness and related to mechanical impedance (Patrick et al., 2001; Stanev and Moustakas, 2019). The more rigid a joint, the more it resists displacement, requiring a larger force in order for movement to occur. Rigidity can occur passively (e.g. in Parkinson's disease, as documented in Sepehri et al., 2007), or actively, principally via AMCC (Nagai et al., 2013). A residual amount of passive rigidity is also implied by muscle tone. In pedagogical contexts, rigidity often carries a negative connotation, similarly as in the case of stiffness—often because the intended pedagogical definition of "rigidity" frequently is "rigidity *in excess* of what is desirable for playing well."	AMCC is the primary means of controlling joint rigidity.
Stiffness	In biomechanical contexts, stiffness can be considered equivalent to rigidity, a quantitative measure of how much a limb resists displacement at a joint—related to mechanical impedance (Patrick et al., 2001; Stanev & Moustakas, 2019). The stiffer a joint, the more its corresponding limb segments resist movement in the same joint (Rouse et al., 2012). For example, a maximally stiff wrist will prevent either the hand or forearm from moving in relation to one another without extreme force; however, both hand and forearm may still be moving in space *together* despite this wrist stiffness, due to (e.g.) a raising or lowering of the entire arm in the glenohumeral joint. Similarly as in the case of rigidity, some residual stiffness occurs due to muscle tone. Further stiffness can occur passively (e.g., due to rigor mortis; see Kobayashi et al., 2004), or actively, in which case it is modulated primarily by AMCC (Borghuis et al., 2008).	AMCC is the primary means of controlling joint stiffness.

Key term	Full rationale and definition	Relevance
	In pedagogical contexts, stiffness often carries a negative connotation—but this appears to be because the intended meaning of "stiffness" in these cases actually is "any stiffness *in excess* of what is required."	
Contraction	In biomechanics, "contraction" typically refers to the act of "shorten[ing] and generating a pulling force" (Gordon et al., 2022, p. 147). Muscle contraction therefore is defined as a muscle's process of activating its fibers to (typically) exert pulling forces on bones via tendinous interconnections; however, 'muscle action' might be a more accurately inclusive descriptor of the phenomenon typically referred to as contraction, because not all muscle activation implies shortening—e.g., in the case of eccentric activation (Hazari et al., 2021). Nevertheless, because "muscle contraction" is a traditional, common term in the biomechanics literature, this article maintains its usage (while acknowledging its limitations, as above)—because the article focuses primarily on AMCC, a *subtype* of muscle contraction (or muscle action). It is worth noting that "contraction," in movement contexts, can also reasonably mean "the process of becoming smaller" (OED)—which implies certain situations of definitional uncertainty that usually go unclarified: for example, Cal03 contrasts "contract" with "expand," implying a valid *alternative* usage (e.g., the muscles in the palm *contracting* (typical meaning) to abduct the fingers, resulting in an *expansion* of the hand's reach; and conversely, the same muscles in the palm *relaxing* to return the fingers to a state of relative adduction, resulting in a *contraction* (alternative meaning) of the hand's reach).	AMCC requires two or more simultaneous, antagonistic contractions.
Suppleness*	The scientific literature lacks a standard definition of suppleness, with researchers adopting varying usages: some equate "suppleness" with "flexibility," i.e., total possible range of motion in a joint (e.g., Al Dhuhaibwi, 2018, p. 10), while others define it as "the possibility of performing	Typically requires dynamic, adaptive AMCC.

Key term	Full rationale and definition	Relevance
	movements with maximum amplitude and ease" (Florina, 2022, p. 145). Suppleness has also been related to "elasticity" by some authors. Given varied scientific usage, it is worthwhile to also consider dictionary definitions of suppleness: for example, the OED defines "supple" as "bending and moving easily and gracefully; flexible; not stiff or hard; easily manipulated," a multifaceted definition that appears to cover more than one of the above scientific usages. Given that "suppleness" has been used as a descriptor alongside "flexibility" by pedagogues for centuries and across multiple languages, it is reasonable to assume that "suppleness" has some distinct meaning *beyond* flexibility. This suggests that "flexibility" on its own is an insufficient definition of "suppleness"—which is corroborated by the OED's multifaceted definition that includes, but is not limited to, "flexible." Clearly, suppleness in the context of human movement demands a certain adaptivity, pliability, or reactivity to applied forces: for example, the teeth cannot be considered especially supple parts of the body, because they significantly resist attempts at deformation until suddenly and irreparably giving way—e.g., by fracturing into pieces when being extracted due to "overzealous extraction technique" (Woodward, 2006, p. 126). This example seems to illustrate an inverse relationship between suppleness and inelasticity (as inelasticity is one means of explaining the above behavior of human teeth), and therefore a positive association between suppleness and elasticity—which *does* have a standard, scientific biomechanical definition (see above). At this point, it is helpful to return to the question of whether "suppleness" is equivalent to "flexibility"—as human teeth are also inflexible, in addition to being not supple, and inelastic. Here, it is necessary to consider further premises—for example, what would constitute something "flexible" and yet "not supple"? Turning our attention temporarily away from the human body,	

Key term	Full rationale and definition	Relevance
	we can consider the case of a wilting plant (e.g., a sunflower in ill health). The stem of such a plant would clearly be, at minimum, somewhat flexible (Rupprecht et al., 2015)—as the plant is wilting (before having completely desiccated, at which point a brittle inflexibility would take over). However, the stem would also be *limp*, due to the plant's ill health; this implies that, if one were to gently deform the stem from its natural shape, it would not readily spring back to its original form, but would instead remain at some stage between its most deformed position and its original state—therefore having higher *plasticity* and lesser *elasticity*. This example illustrates that "flexible" entities are not necessarily "elastic" entities (Zhang et al., 2017)—and therefore supports the notion that "suppleness" implies not only "flexibility" but also "elasticity." It is necessary to consider one further question here: is suppleness therefore simply synonymous with elasticity, given that elastic materials themselves must be flexible? As a final example, consider a rubber cylinder such as those commonly used in physiotherapy (e.g., the THERABAND® FlexBar®, which is made entirely from natural rubber). Rubber is hyperelastic (Beda, 2007), springing back promptly to its original shape after nearly any deformation—but would we consider it supple? We propose the answer is "no, rubber is not supple" (despite occasional descriptions to the opposite effect, e.g., in Rajesh et al., 2018)—because the elasticity of rubber behaves forcefully and suddenly. If one bends a rubber cylinder into a U-shape, and release it adjacent to and in the direction of a wall, the cylinder will (apart from considerations of bending stiffness) snap suddenly back to its cylindrical shape and impact the wall forcibly. Why is this explosive elasticity not compatible with suppleness? Because, as suggested by the OED, "supple" also involves considerations of "ease" and "grace"—which are qualitative variables, not easily defined in mechanical terms, but clearly incompatible with sudden forcefulness.	

Key term	Full rationale and definition	Relevance
	We can now synthesize a loose standard definition of the term, following our prolonged exploration: “suppleness” is “a state of elasticity and flexibility that is characterized by ease and grace.” In biomechanical terms, this definition has a clear connection to the focal concept of this thesis: AMCC, and more specifically, near-optimal, proportionate, *dynamic* AMCC. This form of AMCC is what controls elasticity, which also implies a state that is neither limp (plastic rather than elastic), nor statically stiff (inflexible). It is therefore reasonable to conclude that “suppleness” in human movement is achieved at least in part by dynamic, appropriate AMCC.	
Vibrato*	In scientific usage, “vibrato” typically refers to the rate and extent of pitch modulation in tones produced by pitch-modulatable instruments (Anand, 2012)—e.g., the human voice, the violin, or the flute. The piano is not pitch-modulatable in this sense (typically requiring special equipment and intervention, preferably by a trained technician, in order to change the pitch of the instrument, which is generally impractical during performance), and therefore this usage does not apply here. There is no common scientific usage of “vibrato” more generally in relation to muscle activity or biomechanics, especially outside of references to the muscles responsible for voice-production. The standard dictionary definitions of vibrato are also tied to pitch (e.g., “a rapid, slight variation in pitch in singing or playing some musical instruments, producing a stronger or richer tone” (OED)) and therefore inadmissible here. Therefore, we proceed to derive the following contextual definition of “vibrato” from its etymological origin in Italian, *vibrare*, which means “to vibrate.” In turn, “vibrate” is commonly defined as “to move continuously and rapidly to and fro” (OED). Subsequently, “to and fro” is defined as “in a constant movement backwards and forwards or from side to side” (OED); this quality of back-and-forth can be aptly represented by “oscillate,” which	Implies unavoidable AMCC due to its alternating directions and speed.

Key term	Full rationale and definition	Relevance
	commonly means “move or swing back and forth in a regular rhythm” (OED). We therefore arrive at a loose standard definition of “vibrato,” in contexts of muscle use, as “continuous and rapid oscillation.” This definition is suggestive of the presence of AMCC (Stanier, 1973; Winters & Stark, 1986; Tobalske & Biewener, 2008).	
Resilience*	In scientific contexts, resilience typically relates to the maintenance of mental health via positive adaptation to adverse experiences (Herrman et al., 2011). The term “resilience” does not have a common definition in biomechanical usage. Therefore, we may refer to a standard dictionary definition of resilience: “the capacity to withstand or to recover quickly from difficulties; toughness; the ability of a substance or object to spring back into shape; elasticity” (OED). In relation to biomechanics and the human musculoskeletal system, “to withstand” can imply the ability of a joint to *withstand* forces applied to it without displacement of the corresponding limb segment, while “to recover quickly” can imply the ability of a joint to *quickly* or even *immediately* regain the original position of its corresponding limb segment after a displacement *has* occurred—which is synonymous with joint elasticity, control of which is largely achieved by AMCC (see above). To “spring back into shape” can be interpreted in the same manner, and the OED’s final definition of “resilience” as “elasticity” simply reinforces the premise that “resilience” refers to a state of elasticity. Therefore, we may adopt a loose standard definition of “resilience” in a biomechanical context by slightly narrowing the focus of the OED’s definition: “resilience” here means “the capacity to withstand or recover elastically.” This definition in turn implies that “resilience” and “elasticity” can be treated synonymously—and noteworthily, controlling either implies the presence of AMCC.	AMCC is the primary means of controlling joint resilience.

Note. Terms marked with an asterisk (*) had no common, agreed-upon scientific definition in the context of piano playing, and therefore are given newly formed ‘standard’ definitions here. All other terms are defined by common scientific usage.

Appendix C

List of all included works

Author(s) and contributor(s)	Title	Year	Excerpts
Diruta; Crozier (transl.)	Il Transilvano	1597	3
Bach, C.P.E; Mitchell (transl.)	Essay on the True Art of Playing Keyboard Instruments	1787	4
Schenker; Scott (transl.)	The Art of Performance	ca. 1900	5
Caland; Deppe; Stevenson (transl.)	Artistic Piano Playing as taught by Ludwig Deppe	1903	25
Steinhausen; Rupert (transl.)	The Physiological Errors and Reshaping of Piano Technique	1905	71
Matthay	Relaxation Studies	1908	15
Matthay	Some Commentaries	1911	3
Cooke; Gabrilowitsch; Godowsky; Pauer; Rachmaninoff; Hutchison	Great Pianists on Piano Playing	1913	10
Matthay	Pianoforte Tone Production	1914	48
Hofmann	Piano Playing, with Piano Questions Answered	1920	7
Ortmann	The Physical Basis of Piano Touch and Tone	1925	3
Cortot; Roy-Métaxas (transl.)	Rational Principles of Pianoforte Technique	1928	6
Ortmann	The Physiological Mechanics of Piano Technique	1929	106
Matthay	The Visible and Invisible in Pianoforte Technique	1932	33
Fielden	The Science of Pianoforte Technique	1934	65
Schmitz	The Capture of Inspiration	1935	24
Schultz	The Riddle of the Pianist's Finger	1936	74
Ching	Piano playing, a Practical Method	1946	150
Coviello; Matthay	What Matthay Meant	1948	3
Bonpensiere	New Pathways to Piano Technique	1953	12
Harrison	Piano Technique	1953	5

Author(s) and contributor(s)	Title	Year	Excerpts
Bolton	On Teaching the Piano	1954	2
Ching	The Amateur Pianist's Companion	1956	8
Bowen	The Simplicity of Piano Technique	1961	18
Whiteside	Indispensables of Piano Playing	1961	2
Bacon	Notes on the Piano	1963	12
D'Abreu	Playing the Piano with Confidence	1964	10
Gat	The Technique of Piano Playing	1965	56
Kochevitsky	The art of Piano Playing: A Scientific Approach	1967	14
Bruxner	Mastering the Piano	1972	2
Gieseking and Leimer	Piano Technique	1972	24
Lhévinne	Basic Principles in Pianoforte Playing	1972	5
Wolff; Schnabel	The Teaching of Artur Schnabel	1972	3
Neuhaus	The Art of Piano Playing	1973	12
Kentner	Piano	1976	11
Taylor	The Pianist's Talent	1979	9
Hargrave	The Path to Parnassus	1980	23
Last	Freedom in Piano Technique	1980	7
Bernstein	With Your Own Two Hands	1981	27
Sándor	On Piano Playing	1981	16
Taylor	Principles of Piano Technique and Interpretation	1981	13
Elder; Arrau; Darré; Ohlsson; Kraus; Marcus; Rodriguez	Pianists at Play	1982	16
Philipp	Piano Technique: Tone, Touch, Phrasing and Dynamics	1982	2
Schick; Vengerova	The Vengerova System of Piano Playing	1982	4
Waterman	On Piano Teaching and Performing	1983	1
Newman	The Pianist's Problems	1984	7
Eigeldinger	Chopin: Pianist and Teacher	1986	7
Nicholas; Godowsky	Godowsky: The Pianists' Pianist	1989	1

Author(s) and contributor(s)	Title	Year	Excerpts
Fink	Mastering Piano Technique	1992	41
Dubal; Horowitz	Remembering Horowitz	1993	2
Manshardt; Cortot	Aspects of Cortot	1994	7
Lister-Sink	Freeing the Caged Bird	1995	3
Sherman	Piano Pieces	1996	5
Bruser	The Art of Practicing	1997	27
Ostwald Gould	Glenn Gould	1997	2
Winspur; Parry	The Musician's Hand: A Clinical Guide	1998	19
Conable	What Every Musician Needs to Know about the Body	2000	6
Tubiana; Amadio	Medical Problems of the Instrumentalist Musician	2000	11
Grindea	Healthy Piano Technique	2001	33
Lasserson	Dr. Downing's Piano Technique Doctor	2001	4
Kay; Turvey; Meijer; Bernstein; Popova	An Early Oscillator Model	2003	7
Mark	What Every Pianist Needs to Know about the Body	2004	57
Taubman; Golandsky; Bloomfield; Yagupsky; Urvater	Virtuosity in a Box	2005	10
Walker; Liszt	Reflections on Liszt	2005	1
Altenmüller; Kesselring; Wiesendanger; Jabusch	Music, Motor Control and the Brain	2006	1
Soderlund; Thalberg	How Did they Play? How Did They Teach? A History of Keyboard Technique	2006	4
Barnes; Feinberg; Goldenweiser; Oborin; Igumnov	The Russian Piano School	2007	10
Gerig; Kalkbrenner; Saint-Saëns; Liszt; Mason; Deppe; Lhévinne; Long; Debussy; Carreño; Breithaupt;	Famous Pianists & Their Technique	2007	81

Author(s) and contributor(s)	Title	Year	Excerpts
Leonard; Townsend; Matthay; Fielden; Ortmann; Schultz			
Grindea; Perlemuter; Sherman; Bolet; Gerig; Vásáry; Lill; Smith; Wild; True; Ohlsson	Great Pianists and Pedagogues	2007	22
Knudson	Fundamentals of Biomechanics	2007	1
Walker; Bülow	Hans von Bülow: A Life and Times	2010	2
Fraser	The Craft of Piano Playing	2011	145
Abernethy	Biophysical Foundations of Human Movement	2013	1
Wallick	Piano Practice	2013	4
Karpeyev; Meitner	New Light on Nikolay Medtner as Pianist and Teacher	2014	1
Roberts; Beethoven	How the Pianist's Touch Affects Tone Quality	2014	7
Stannard	Piano Technique Demystified	2014	2
Deahl; Wristen	Adaptive Strategies for Small-handed Pianists	2017	21
Lister-Sink	Lister-Sink Method Teacher Training Manual	2018	2
Doran; Liszt	Liszt and Virtuosity	2020	1
Koumis	Mind + Body + Piano	2020	11

Appendix D

List of unretrieved pedagogical works

Barnard, T., & Zocchi, R. (Eds.). (1996). *A guide to the study of solo piano repertoire at tertiary level*. University of Melbourne.

Breithaupt, R. M., & Bernhoff, J. (1909). *Natural piano-technic: school of weight-touch: a practical preliminary school of technic teaching the natural manner of playing by utilizing the weight of the arm: Preliminary to intermediate grade. Vol. II*. C.F. Kahnt Nachfolger.

Burrowes, J. F. (1841). *A guide to practice on the piano forte*. The Author.

Ching, J. (1927). *Muscular relaxation: A simple explanation*. Forsyth Bros., Ltd.

Ching, J. (1934). *Piano technique: Foundation principles.*

Czerny, C., & Badura-Skoda, P. (1970). *On the proper performance of all Beethoven's works for the piano*. Universal Edition.
Dent, E. J. (1966). *Ferruccio Busoni: A biography*. Clarendon.
Dunn, J. P. (1933). *The basis of pianoforte playing*. Oxford University Press, H. Milford.
Eddie, W. A. (2007). *Charles Valentin Alkan: His life and his music*. Ashgate.
Engel, C. (1853). *The pianist's hand-book: A guide for the right comprehension and performance of our best pianoforte masters*.
Fang, S.-W. C. (1978). *Clara Schumann as teacher*. University of Illinois.
Göllerich, A., Jerger, W., & Zimdars, R. L. (1996). *The piano master classes of Franz Liszt, 1884-1886: Diary notes of August Göllerich*. Indiana University Press.
Gunton, S. (2008). *Brahms's 51 Übungen and their unique role in the evolution of piano technique*. Royal College of Music.
Hipkins, E. J., & Hipkins, A. J. (1937). *How Chopin played: From contemporary impressions*. J. M. Dent.
Holloway McArthur, V. (1987). *An application of instructional task analysis and biomechanical motion analysis to elementary cognitive and psychomotor piano learning and performance*. Florida State University.
Hope, E. (1962). *Aids to technique: Muscular development exercises for pianists and other instrumentalists*. Edwin Ashdown.
Huntley, N. (1982). *The hidden variables of pianoforte technique and the fundamentals of skill*. Prescience Publications.
Hutchins, C. M. (Ed.). (1978). *The physics of music: Readings from Scientific American*. W. H. Freeman.
Langley, G. (1902). *Pianoforte students' chart of technique and theory*. Augener & Co.
Last, J. (1960). *The young pianist: A new approach for teachers and students (4th impression (rev.))*. Oxford University Press.
Lindo, A. H. (n.d.). *Pianoforte study: Hints for teachers & students*. Augener.
Long, M. (1980). *At the piano with Fauré*. Kahn & Averill.
Moisey, A. (n.d.). *The solo piano music of Igor Stravinsky: Aspects of technique and interpretation*.
Noyle, L. J. (Ed.). (1987). *Pianists on playing: Interviews with twelve concert pianists*. Scarecrow Press.
Pearce, C. W. (1910). *The art of the piano teacher: Viewed from its physical, psychological and practical standpoints* (8th ed). Winthrop Rogers.
Pfeiffer, T., Zimdars, R. L., Motta, J. V. da, & Bülow, H. von. (1993). *The piano master classes of Hans von Bülow: Two participants' accounts*. Indiana University Press.
Philipp, I. (1927). *Some reflections on piano playing*. A. Durand.
Roberts, P. (2012). *Reflections: The piano music of Maurice Ravel*. Amadeus Press.
Roskell, P. (2020). *The complete pianist*. Edition Peters.
Taylor, F. (1899). *Primer of pianoforte playing*. Macmillan.
Taylor, W. F. (n.d.). *Technique and expression in pianoforte playing*. Novello.
Townsend, W. (1903). *Balance of arm in piano technique*. Bosworth.
Vieira, J. (n.d.). *A survey of fitness wellbeing and injury among piano students*.
Wolff, K. (1983). *Masters of the keyboard: Individual style elements in the piano music of Bach, Haydn, Mozart, Beethoven, and Schubert*. Indiana University Press.

Supplementary materials

- Longform of all critiques: https://journalofpianoresearch.org/wp-content/uploads/2026/10/Ashkenazi-Williamon-Waddell-Longform-of-all-critique.pdf
- Complete AMCC model: https://journalofpianoresearch.org/wp-content/uploads/2026/10/Ashkenazi-Williamon-Waddell-Populated-complete-model.pdf
- Complete dataset: https://journalofpianoresearch.org/wp-content/uploads/2026/10/Ashkenazi-Williamon-Waddell-Labeled-complete-dataset.xlsx