Journal of Medical and Biological Engineering (2023) 43:749–757
https://doi.org/10.1007/s40846-023-00835-7

ORIGINAL ARTICLE

Practically Feasible Sensor-Embedded Kinetic Assessment Piano System for Quantifying Striking Force of Digits During Piano Playing

Kuan-Yin Lai[1] · Chieh-Hsiang Hsu[1,2] · Yu-Chen Lin[3] · Chung-Hung Tsai[4,5] · Cheng-Feng Lin[6] · Li-Chieh Kuo[1,2,5,7] · Fong-Chin Su[1,7]

Received: 21 August 2023 / Accepted: 18 October 2023 / Published online: 7 November 2023

Abstract

Purpose Understanding the pathogenesis of playing-related hand disorders through investigations based on coordination and biomechanical perspectives is indispensable. This study aimed to establish a sensor-embedded kinetic assessment piano system (SeKAPS) and conduct reliability and validity tests for this system. In addition, the differences in digit coordination between professional pianists and non-musicians were investigated.

Methods Twelve subminiature load cells were embedded in the middle of the 12 corresponding keys of an upright piano. A customized calibrated system with a load cell was used to establish the criterion-related validity of the SeKAPS. The reliability of the SeKAPS was determined by 22 volunteer pianists. The other ten professional pianists and ten non-musicians were recruited to indicate the feasibility of the SeKAPS to distinguish the performing differences between groups.

Results The R^2 values of regression analyses for the load cells were 0.993–0.999 ($p < 0.001$), indicating high validity. The ICC values of the modified keys were 0.82–0.93, indicating high reliability. The results indicate that SeKAPS is accurate in detecting the striking force of digits during piano playing. Significant differences existed in the mean peak force and mean CVs of the peak force of the specific digits between the two groups. The results showed differences in finger control strategies between the pianists and non-musicians.

Conclusion The SeKAPS may provide a valuable assessment for assisting pianists in understanding digit force control and movement strategies to achieve efficient digit coordination.

Keywords Pianists · Digit coordination · Kinetic measurement · Sensors · Piano

✉ Li-Chieh Kuo
jkkuo@mail.ncku.edu.tw

✉ Fong-Chin Su
fcsu@mail.ncku.edu.tw

1 Department of Biomedical Engineering, College of Engineering, National Cheng Kung University, Tainan 701, Taiwan

2 Department of Occupational Therapy, College of Medicine, National Cheng Kung University, Tainan 701, Taiwan

3 Department of Occupational Therapy, Da-Yeh University, Changhua, Taiwan

4 Department of Family Medicine, An-Nan Hospital, China Medical University, Tainan, Taiwan

5 Institute of Allied Health Sciences, College of Medicine, National Cheng Kung University, Tainan, Taiwan

6 Department of Physical Therapy, College of Medicine, National Cheng Kung University, Tainan, Taiwan

7 Medical Device Innovation Center, National Cheng Kung University, Tainan, Taiwan

1 Introduction

Playing piano requires highly skilled and coordinated hand movements. However, pianists often suffer from playing-related musculoskeletal disorders [1–11] because of rapid and repetitive movements of the wrist and hand for an extended period. These movements lead to symptoms such as pain, weakness, and numbness of the hand, particularly the thumb, ring, and little fingers [3, 12–19]. Studies on the biomechanical performance of pianists have been emphasized since the late 1920s. The literature on kinematic studies of pianists is still insufficient, and there is a lack of strong evidence and rationale to address the importance of the relationship between kinematics and piano-playing-related injuries. Only a few studies have investigated hand postures and finger movements of pianists while playing assigned musical compositions using electrogoniometers, camcorders, or three-dimensional motion capture systems [20–27]. Lee examined the relationships between anthropometry and kinematics, such as the hand length, hand width, finger length, active finger span, wrist ulnar deviation, and hand weight, with the performance of a scale in thirds [28]. However, these studies focused on investigating the performance of a single joint or segment without a comprehensive or systematic analysis of hand performance during piano playing [29].

Moreover, it is worth investigating the effect of the reaction forces on the movements of the thumb or fingers during striking computer keyboards and piano keys because many hand injuries result from unbalanced contact forces between the digits and objects in awkward postures. Early tools that were typically used to inspect the force exerted by the hand included dynamometers and strain-gauge-instrumented transducers. Electromyography was introduced in modern experimental studies [30, 31] to detect muscular contraction forces of the limbs during playing movements [20, 32–35]. Several studies have investigated fingertip force or pressure on piano keys using piezoelectric force transducers, pressure sensors, and strain-gauge-type miniature force transducers [36–41]. However, these studies measured the force exerted on the sensor on one key or the sensor be applied in the key-bed. These methods have limited ability in precisely estimating the actual finger striking force exerted on piano keys while playing the piano. Without this information, the relationships between the striking force, movement mechanism, and disease pathogenesis might be difficult to determine objectively. Thus, it is essential to develop appropriate quantitative methods for directly measuring the striking force from the digits to clarify the mechanism of playing performance and analyze the relationship between digit coordination and playing-related injuries. In addition, piano playing is a bimanual finger movement affected by tempo; therefore, it is necessary to investigate the digit coordination and control mechanisms of both hands under various tempi.

Investigations based on kinetic measures are critical for examining the mechanism of playing performance and revealing the relationship between digit coordination and playing-related injuries to thoroughly understand the digit coordination of fundamental movements during piano playing. To the best of our knowledge, suitable apparatuses for measuring the finger-striking forces during piano performances are limited. Therefore, this study attempted to investigate the complexity of digit coordination based on an elaborately designed device by embedding force transducers in regular upright piano keys. A novel force-detection system for piano keys that could record the striking force immediately while preserving most of the original piano features was established. Psychometric properties of the system, such as validity and reliability tests, were conducted to measure the applicability of this novel system. In addition, the variability of the acquired kinetic information was determined. Furthermore, this study aimed to investigate the differences in digit coordination and kinetic performance between professional pianists and non-musicians while performing basic piano fingerings using this force detection system.

2 Methods

2.1 Development of Sensor-Embedded Kinetic Assessment Piano System (SeKAPS)

2.1.1 Hardware and Software Establishment of SeKAPS

For the standard piano fingering, twelve subminiature load cells (SLB-25, 6.35 mm height, 9.53 mm diameter, Transducer Techniques, CA, USA) were embedded in the middle of the 12 corresponding keys of an upright piano (Fig. 1). Each load cell was held between two linear bearings to ensure stability (Fig. 1C). Twelve white keys (C2, C3-G3, C4-G4, and C5) were modified (Fig. 1E). The white key without a keytop was refitted from being embedded in the load cell. The key step was milling to embed the load cell, wires, and linear bearings. An aluminum pad was designed to transduce the strike force to the load cell. The sticks and bearings were used to ensure the vertical movement of the aluminum pad. To maintain the original physical features of these modified keys, a trimmed front white keytop was attached to the aluminum pad, and the weight was added with lead at the end of the white key.

Analog force data were obtained from a customized amplifier connected to a NIDAQ device (PCI-6723, National Instruments Corp., USA). The sampling rate was 1000 Hz. The load cells embedded in the keys were calibrated with standard weights using regression analysis. Weight calibration was performed using standard weights of 50, 100, 200, 300, 600, 800, 1100, 1300, and 1600 g. Each sample was weighed three times with each standard weight.

2.1.2 Validity of SeKAPS

A customized calibrated system with a load cell (MDB-50, Transducer Techniques, CA, USA) was fixed to a pneumatic linear actuator with a height-adjustable frame to establish the criterion-related validity of the load cells embedded in the modified piano keys. During calibration with a load cell, the fixture with the MDB-50 load cell rapidly moved downward to exert a downward force on each load cell of SLB-25 embedded in the piano keys (Fig. 2) to simulate key striking during piano playing. The force outputs from the load cell of SLB-25 and the calibrated reference with a load cell were collected simultaneously. The force data from the SLB-25 load cell were obtained using a calibrated reference with a load cell.

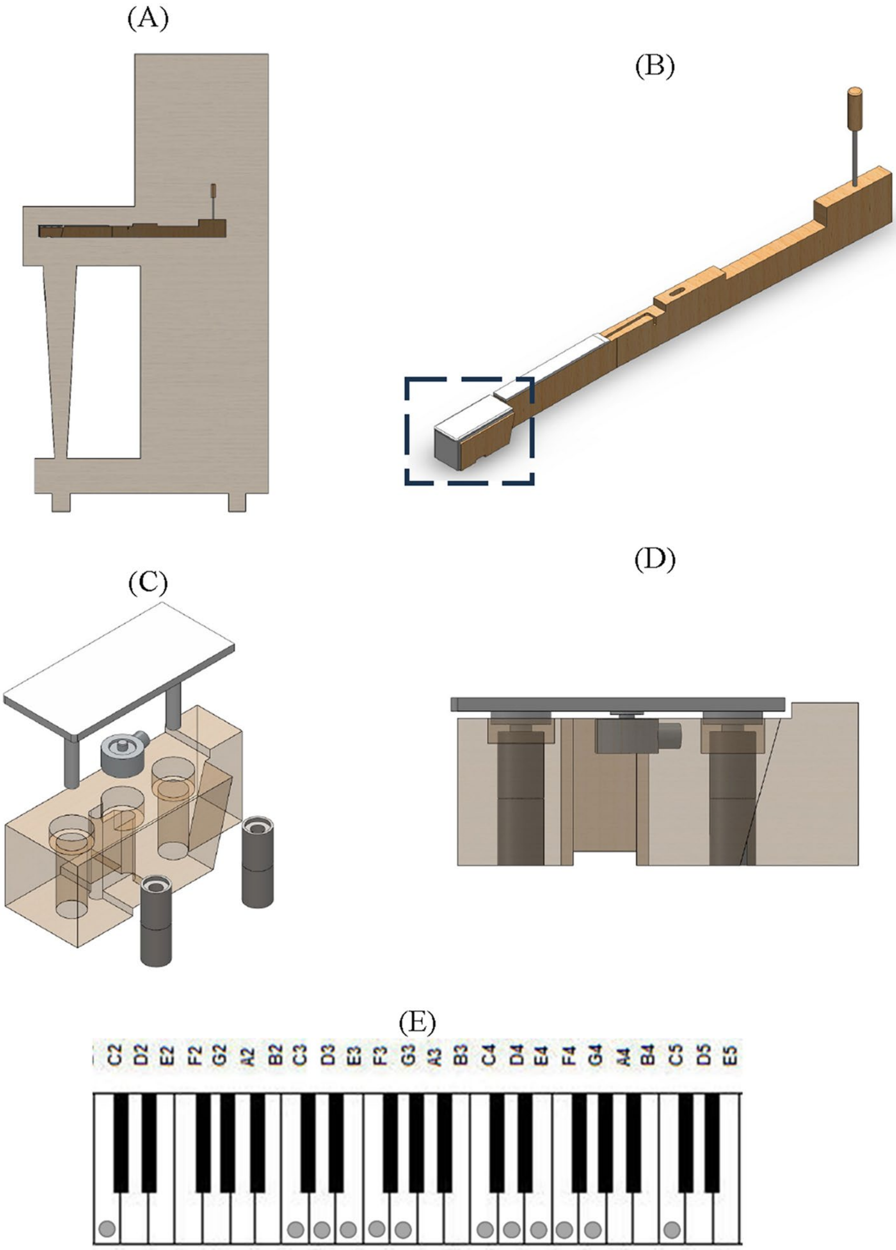

Fig. 1 **A** The sideview of *SeKAPS*. **B** The structure of the modified key. **C** The exploded view of force detecting part that containing load cell, linear bearings and aluminum pad. **D** The sideview of the force detecting part. **E** Each load cell was embedded in 12 white keys (C2, C3-G3, C4-G4, and C5)

2.1.3 Reliability of SeKAPS

The reliability of the 12 modified keys were determined by 22 healthy young volunteers (3 males, 19 females, mean age ± SD: 26.59 ± 3.55 years) with an average of 6.23 ± 3.24 years of piano-learning experience. All the participants were right-handed and had no history of a hand injury, surgery, or neurological deficits. All the participants were informed about the purpose of the study, and a signed, informed consent form approved by the Institutional Review Board of the National Cheng Kung University Hospital was obtained from each participant prior to the experiment.

Before the measurements, each participant sat upright on an adjustable piano bench in front of the modified piano keys. Each participant was requested to demonstrate the following types of basic piano skills: (1) scale, a set of musical notes ordered by an ascending pitch and a descending pitch; (2) octave, eight intervals between two music pitches (C4 and C5) for five cycles (Fig. 3). Each piano skill was performed using the right hand, followed by the left hand. Each skill performance was repeated three times in an interval of 5 s with a rest period of approximately 30 s. All the participants were evaluated on three testing days, with a one-week interval between the testing days. The striking forces on the

Fig. 2 Customized calibrated system with load cell of MDB-50

modified keys were recorded during piano playing to examine the reproducibility of the 12 modified piano keys.

2.1.4 Variability of SeKAPS

Variability is used to estimate measurement error or stability. Variability is quantified as the coefficient of variance (CV), defined as the ratio of the standard deviation to the mean, and expressed as a percentage. A low CV indicates consistent responses from the measurements.

2.2 Human In Vivo Experiments for SeKAPS

Ten professional pianists and ten non-musicians were recruited for this study. The following inclusion criteria for professional pianists were applied: (a) students majoring in piano at the College of Music, (b) self-employed piano teachers with a college degree in music, (c) participants with more than 10 years of piano-playing experience, and (d) participants with no neurological deficit, hand musculoskeletal diseases, nor history of hand surgery. The exclusion criteria for the non-musicians included participants with experience in playing any musical instrument and non-musicians with neurological deficit, hand musculoskeletal diseases, or history of hand surgery.

The participants were instructed to sit on a chair facing the modified piano. Prior to the testing session, each participant was assigned to perform two piano skills: the octave (fingering 1^r5^r-1^r5^r-1^r5^r-1^r5^r-1^r5^r; 1^l5^l-1^l5^l-1^l5^l-1^l5^l-1^l5^l) and chord (fingering $1^r3^r5^r$-$1^r3^r5^r$-$1^r3^r5^r$-$1^r3^r5^r$-$1^r3^r5^r$; $1^l3^l5^l$-$1^l3^l5^l$-$1^l3^l5^l$-$1^l3^l5^l$-$1^l3^l5^l$) (Fig. 4).

Each skill was performed first with the right hand and then with the left hand. The participants practiced for approximately 15 min. This study employed a metronome to cue the tempo during each trial. The skills were performed at T140 (140 beats/min) on a quarter note. The participants were instructed to play synchronously with the beat of the metronome. In addition, the target loudness of the tone was set to approximately 95 dB using a sound level meter to control the force applied uniformly by all participants. All skills were exhibited with a Legato touch. The striking forces of the digits acting on each modified key were continuously recorded for each skill. For the between-group analysis, the obtained peak force was calculated as the mean value and CV within one trial.

2.3 Statistical Analysis

Statistical analyses were conducted using SPSS 17.0 software (SPSS Inc., Chicago, Illinois, USA). Descriptive statistics were used to calculate the mean and standard deviation (SD) values of demographic data. Regression analysis was used for the validity test. The intraclass

Fig. 3 Two basic skills used in reliability test: **A** chord, **B** octave

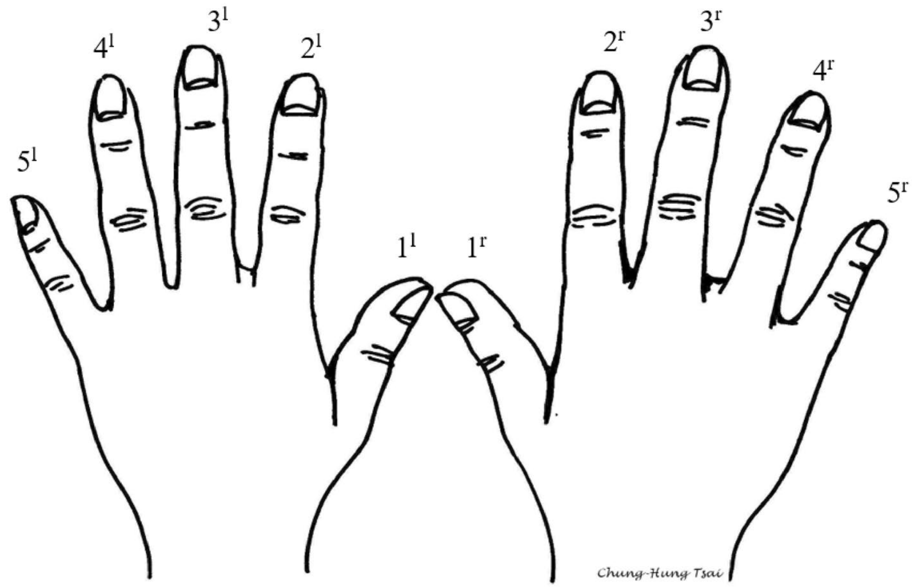

Fig. 4 Name of fingering on bilateral hands

correlation coefficient (ICC) was used to test the reliability of the striking force. The ICC was calculated using variance estimates obtained via the analysis of variance from all trials during the three visits. Variability can be used to estimate measurement errors. Variability was quantified as the CV, defined as the ratio of the standard deviation to the mean, and expressed as a percentage. A lower CV indicated consistent responses from the measurements. Therefore, CV can be used to assess the response stability across repeated trials for each modified key. The Mann–Whitney *U*-test was used to assess between-group differences. The level of statistical significance was set at $p < 0.05$.

3 Results

3.1 Validity, Reliability, and Variability of SeKAPS

The R^2 values of the regression analyses for the 12 load cells were 0.993–0.999 ($p < 0.001$), indicating high validity of the SeKAPS. The ICC values of the 12 modified keys were 0.82–0.93 (Table 1), indicating the high reliability of the SeKAPS.

For the variability test, the mean CV of all participants among the three trials ranged from 13 to 24% while playing the scale, and from 5 to 24% while playing the octave. The results showed that the repeated measurement variations were within the satisfactory range. In other words, the stability of the responses measured from the 12 modified keys was acceptable.

Table 1 ICC value and 95% C.I. of each modified key while playing scale and octave on one-week-interval repeated measures

Modified keys	Basic piano skills			
	Scale		Octave	
	ICC	95% C.I.	ICC	95% C.I.
C2			0.904	0.805–0.957
C3	0.864	0.724–0.939	0.903	0.803–0.957
D3	0.929	0.856–0.939		
E3	0.912	0.820–0.961		
F3	0.902	0.801–0.956		
G3	0.862	0.720–0.939		
C4	0.819	0.632–0.919	0.931	0.860–0.969
D4	0.876	0.749–0.945		
E4	0.880	0.756–0.946		
F4	0.908	0.814–0.959		
G4	0.869	0.734–0.941		
C5			0.915	0.828–0.962

C3, D3, E3, F3, G3, C4, D4, E4, F4, and G4 are the scale keys

C2, C3, C4, *and* C5 *are the octave keys*

ICC intraclass correlation coefficient

C.I. confidence interval

3.2 Human In Vivo Experiments for SeKAPS

Twenty right-handed female participants were recruited for this study. The mean age of the professional pianist group was 20.3 ± 1.6 years, with an average piano-learning experience of 13.7 ± 2.2 years. The mean age of the non-musician group was 22.4 ± 2.3 years.

Significant differences in the mean peak force of the right and left little fingers between the non-musician and professional pianist groups were observed while playing the chords. There was a significant difference in the mean CV of the peak force of the right and left middle and little fingers between the two groups. In addition, the results showed a significant difference in the mean CVs of the peak force of the left thumb and little finger between the two groups (Table 2).

4 Discussion

Pianists perform repetitive multifinger force production movements while playing the piano. Pianists typically use their both hands to play complex melodies and perform faster repetitive finger movements and more forceful striking of keys while playing piano. A pianist aims to achieve good control of each digit on the key with appropriate striking force and fewer playing mistakes. Therefore, finger coordination plays a critical role in playing the piano. Thus, an adequate apparatus is required to objectively and precisely measure the forces acting on piano keys. The SeKAPS was designed and established to measure the striking force of a pianist's digits when playing the piano.

It is crucial to determine the reliability of a newly designed apparatus and validate the data acquisition accuracy. The force generated by a fixture with a calibrated reference load cell was used to verify the validity of SeKAPS. The results showed high R^2 values (> 0.99), indicating that the 12 load cells embedded in the modified piano keys of the upright piano accurately recorded the actual striking force. Thus, the striking forces of the digits applied to the load cells embedded in the modified keys were recorded precisely. For the reliability test, the ICC results showed good repeatability of measurements on the one-week-interval testing days. The mean CV values for all the participants in the three trials were stable, with slight variability in the measured responses. This indicates consistency in the striking force for repeated SeKAPS trials during piano playing.

The SeKAPS investigated the digit force of 10 professional pianists and 10 non-musicians while playing chords and octaves to detect the actual finger force during piano playing.

The results of the in vivo test showed that the little finger striking force of professional pianists exceeded that of the non-musicians. Because the little finger plays a supportive role in grasping and manipulating movements, the little-finger striking force of the non-musicians was weak.

However, professional pianists may enhance the force and coordination of their little fingers through finger exercises while playing the piano. Therefore, the difference in the mean peak force of the little finger between the two groups indicates superior finger motor control in professional pianists.

In addition, the discrepancy in the finger-stroke characteristics during piano playing between professional pianists and non-musicians was examined using the CV value. The CV results showed that the finger-stroke stability of the professional pianist group during piano playing was better than that of the non-musician group, particularly the middle finger and little finger of the bilateral hands during chord play and the thumb and little finger during octave play. During piano training, professional pianists may perform different dynamics written on musical sheets, such as pianissimo (*pp*) or fortissimo (*ff*). *pp* indicates that the pianists should play

Table 2 Results of Mann–Whitney *U*-test between pianists and non-musicians while playing chord and octave

	Peak mean			Peak C.V.		
	NS ($n=10$)	PS ($n=10$)	*p*-value	NS ($n=10$)	PS ($n=10$)	*p*-value
Chord						
R_thumb	3.68 ± 1.66	4.02 ± 1.35	0.43	0.13 ± 0.03	0.09 ± 0.04	0.09
R_middle finger	4.34 ± 1.51	4.70 ± 2.08	0.57	0.12 ± 0.05	0.07 ± 0.04	0.02*
R_little finger	2.79 ± 0.89	4.19 ± 1.46	0.01*	0.21 ± 0.10	0.08 ± 0.03	0.00**
L_thumb	3.49 ± 1.15	4.24 ± 1.50	0.19	0.11 ± 0.08	0.09 ± 0.03	0.21
L_middle finger	5.82 ± 2.03	5.15 ± 1.45	0.68	0.15 ± 0.07	0.10 ± 0.04	0.01*
L_little finger	2.60 ± 1.14	3.71 ± 1.04	0.01*	0.21 ± 0.13	0.10 ± 0.04	0.03*
Octave						
R_thumb	4.47 ± 1.11	5.49 ± 2.15	0.47	0.13 ± 0.04	0.09 ± 0.05	0.14
R_little finger	4.16 ± 1.44	5.08 ± 1.61	0.16	0.09 ± 0.05	0.07 ± 0.04	0.14
L_thumb	5.19 ± 1.62	6.67 ± 2.65	0.27	0.11 ± 0.06	0.09 ± 0.04	0.05*
L_little finger	5.28 ± 1.57	5.89 ± 1.54	0.73	0.11 ± 0.05	0.06 ± 0.02	0.02*

Unit: Newton

C.V. coefficient of variance, *NS* nonmusicians, *PS* professional pianists, *R* right, *L* left

Significance: $^{*}p < 0.05$ (two-tailed), $^{**}p < 0.01$ (two-tailed) very quietly, whereas *ff* time indicates that they should play very loudly. Therefore, professional pianists usually have better force control of each finger during piano playing than non-musicians. Through SeKAPS measurements, this study highlighted the differences in finger motor control between professional pianists and non-musicians.

Fernandes and Barros investigated finger coordination based on a gross-grip task using a kinematic analysis and observed that pianists exhibited better motor control than non-musicians [42]. Oku and Furuya examined the difference in key force between classical pianists and musically untrained individuals using a strain-gauge miniature uniaxial-force transducer at the distal end of one key. The results showed that pianists had better finger-stroke stability than non-musicians at slow tempi. However, their study only measured a single finger force once [39]. In our study, the SeKAPS with 12 load cells could measure the finger force of 12 keys simultaneously while demonstrating different piano skills. Therefore, compared with previous studies, the SeKAPS in this study is a comprehensive representation of the actual force of each finger during piano playing. It also demonstrates the performance of motor control for different piano skills.

The literature reveals that piano-related hand injuries include tendonitis, de Quervain's disease, 2nd–5th flexor tenosynovitis, as well as various peripheral nerve entrapment syndromes such as carpal tunnel syndrome and ulnar neuropathy [25]. In order to obtain a comprehensive understanding of the injury mechanism and disease pathogenesis, it is imperative to investigate the impact of finger reaction forces while striking the piano keys. The clinical importance of this study is to build an evaluation tool, SeKAPS, which can demonstrate the force control of each digit of pianists. Furthermore, pianists can adjust the digit movement strategies via SeKAPS to prevent playing-related hand injuries.

The limitation of the SeKAPS design is that the load cells embedded in the key only measure the finger-striking force in the normal direction without considering playing-related shear forces. In addition, SeKAPS has a non-portable design; therefore, it may not be used at all times and places without modifying the piano. Moreover, only 10 professional pianists and 10 non-musicians were examined in the in vivo test of this study. The limited number of participants might have been insufficient to comprehensively represent the features of these two populations. More participants should be included in future studies. Furthermore, only female participants were recruited in the part of human in vivo experiments for SeKAPS in this study, resulting in a lack of data on the playing performance of male participants. In future studies, the number of modified keys with load cells should be increased to obtain more concrete evidence related to finger control while playing piano pieces. Furthermore, future studies should adopt time-related variables of key striking.

Previous research did not empirically describe the complex mechanics of piano playing; thus, it failed to represent the finger stroke characteristics among all digits during piano playing, including the actual striking force of each digit. In this study, the customized SeKAPS system embedded with 12 load cells enabled the accurate measurement of the finger-striking force during piano playing. This system can also represent the finger coordination when exhibiting different piano skills. SeKAPS data directly provide motor control strategies, enhancing the effectiveness of piano training protocols for pianists. Moreover, it can serve as an evaluation tool for clinicians and therapists in understanding the mechanics of playing-related musculoskeletal injuries in pianists.

Acknowledgements This study was funded by the National Science and Technology Council (NSTC) of TAIWAN (Grant No. 98-2320-B-006-003-MY3). This work was also partially supported by the Medical Device Innovation Center, National Cheng Kung University, from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project of the Ministry of Education (MOE) in Taiwan. The authors would also like to thank Mr. Cheng-Chun Chen for his kind assistance with several technical aspects of this study.

Author Contributions KYL, LCK, and FCS were the principal contributors to the study design, data collection, and assessment. KYL, YCL, CHH, CFL, LCK, and FCS performed technical problem-solving in the experiments. KYL, CFL, and CHT participated in the registration and clinical examinations of the participants. KYL, YCL, CHH, LCK, and FCS participated in the data analysis and interpretation. KYL, YCL, CHH, and LCK drafted the manuscript. All the authors read and approved the content and format of the final manuscript.

Funding We certify that no party with a direct interest in the results of this study has or will confer a benefit on us or any organization with which we are associated. We also certify that all financial and material support for this research (for example, governmental grants) and work are clearly identified on the title page of the manuscript.

Data Availability IRB No. B-ER-104-160 - approved by the Institutional Review Board of the National Cheng Kung University Hospital. The datasets analyzed during the current study are not publicly available due to data protection requirements, but anonymous data or files could be available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no potential conflicts of interest with respect to the research design, experiments, authorship, or publication of this article.

Ethical Approval All procedures involving human participants in this study were performed in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The procedures and consent forms used in this study were reviewed and approved by the Institutional Review Board of National Cheng Kung University Hospital in Taiwan.

Informed Consent Informed consent was obtained from all the participants recruited in this study.

References

1. Bragge, P., Bialocerkowski, A., & McMeeken, J. (2006). A systematic review of prevalence and risk factors associated with playing-related musculoskeletal disorders in pianists. *Occupational Medicine*, *56*, 28–38. https://doi.org/10.1093/occmed/kqi177.
2. Bragge, P., Bialocerkowski, A., & McMeeken, J. (2006). Understanding playing-related Musculoskeletal disorders in Elite pianists: A grounded theory study. *Medical Problems of Performing Artists*, *21*(2), 71–79. https://doi.org/10.21091/mppa.2006.2014.
3. De Smet, L., Ghyselen, H., & Lysens, R. (1998). Incidence of overuse syndorme of the upper limb in young Piansit. *Annals of Hand and Upper Limb Surgery*, *17*(4), 309–313.
4. Ling, C. Y., Loo, F. C., & Hamedon, T. R. (2018). Playing-related Musculoskeletal disorders among classical piano students at Tertiary Institutions in Malaysia: Proportion and Associated Risk factors. *Med Probl Perform Art*, *33*(2), 82–89. https://doi.org/10.21091/mppa.2018.2013.
5. Rosety-Rodriguez, M., et al. (2003). The influence of the active range of movement of pianists' wrists on repetitive strain injury. *Eur J Anat*, *7*(2), 75–77.
6. Zaza, C. (1998). Playing-related musculoskeletal disorders in musicians: A systematic review of incidence and prevalence. *Canadian Medical Association Journal*, *158*(8), 1019–1025.
7. Zaza, C., & Farewell, V. T. (1997). Musicians' playing-related musculoskeletal disorders: An examination of risk factors. *American Journal of Industrial Medicine*, *32*(3), 292–300.
8. Baadjou, V. A. E., et al. (2016). Systematic review: Risk factors for musculoskeletal disorders in musicians. *Occupational Medicine (Oxford, England)*, *66*(8), 614–622. https://doi.org/10.1093/occmed/kqw052.
9. Cruder, C., et al. (2020). Prevalence and associated factors of playing-related musculoskeletal disorders among music students in Europe. Baseline findings from the risk of music students (RISMUS) longitudinal multicentre study. *PLoS One*, *15*(12), e0242660. https://doi.org/10.1371/journal.pone.0242660.
10. Baeyens, J. P., et al. (2022). Effects of Rehearsal Time and Repertoire Speed on Upper trapezius activity in Conservatory piano students. *Med Probl Perform Art*, *37*(1), 1–12. https://doi.org/10.21091/mppa.2022.1001.
11. Xiaoyu, M., & Musib, A. F. B. H. (2023). Study on the prevalence and prevention measures of Musculoskeletal diseases in Chinese piano students. Eurasian Journal of Educational Research, 103(103).
12. Ashish Mathew, A., & Farzana, S. F. M. (2021). Prevalence of Musculoskeletal disorder in wrist and Fingers amomg amateur piano players in Vellore. *Indian Journal of Forensic Medicine & Toxicology*, *16*(1), 259–266. https://doi.org/10.37506/ijfmt.v16i1.17462.
13. Blackie, H., Stone, R., & Tiernan, A. (1999). An investigation of injury prevention among university piano students. *Medical Problems of Performing Artists*, *14*(3), 141–149.
14. Furuya, S., et al. (2006). Prevalence and causal factors of playing-related Musculoskeletal disorders of the Upper extremity and trunk among Japanese pianists and piano students. *Medical Problems of Performing Artists*, *21*(3), 112–117. https://doi.org/10.21091/mppa.2006.3023.
15. Goodman, G., & Staz, S. (1989). Occupational therapy for musicians with upper extremity overuse syndrome: Patient perceptions regarding effectiveness of treatment. *Medical Problems of Performing Artists*, *4*(1), 9–14.
16. Pak, C. H., & Chesky, K. (2001). Prevalence of Hand, Finger, and wrist Musculoskeletal problems in keyboard instrumentalists. *Medical Problems of Performing Artists*, *16*(1), 17–23.
17. Sakai, N. (1992). Hand pain related to keyboard techniques in pianists. *Medical Problems of Performing Artists*, *7*(2), 63–65.
18. Sakai, N. (2002). Hand Pain attributed to overuse among Professional pianists. *Medical Problems of Performing Artists*, *17*(4), 178–180.
19. Shields, N., & Dockrell, S. (2000). The prevalence of injuries among pianists in music schools in Ireland. *Medical Problems of Performing Artists*, *15*(4), 155–160. https://doi.org/10.21091/mppa.2000.4030.
20. Bejjani, F. J., et al. (1989). Comparison of three piano techniques as an implementation of a proposed experimental design. *Medical Problems of Performing Artists*, *4*(3), 109–113.
21. Chung, I. S., et al. (1992). Wrist motion analysis in pianists. *Medical Problems of Performing Artists*, *7*(1), 1–5.
22. Ferrario, V. F., et al. (2007). Three-dimensional analysis of Hand and Finger movements during piano playing. *Medical Problems of Performing Artists*, *22*, 18–23. https://doi.org/10.21091/mppa.2007.1004.
23. Sakai, N., et al. (1996). Motion analysis of the fingers and wrist of the pianist. *Medical Problems of Performing Artists*, *11*(1), 24–29.
24. Sakai, N., et al. (2006). Hand span and digital motion on the keyboard: Concerns of overuse syndrome in musicians. *The Journal of Hand Surgery*, *31*(5), 830–835. https://doi.org/10.1016/j.jhsa.2006.02.009.
25. Turner, C., et al. (2021). Pursuing Artful Movement Science in Music Performance: Single subject motor analysis with two Elite pianists. *Perceptual and Motor Skills*, *128*(3), 1252–1274. https://doi.org/10.1177/00315125211003493.
26. Wristen, B. G., et al. (2006). Assessment of muscle activity and joint angles in small-handed pianists: A pilot study on the 7/8-Sized keyboard versus the full-sized keyboard. *Medical Problems of Performing Artists*, *21*(1), 3–9. https://doi.org/10.21091/mppa.2006.1002.
27. Lai, K. Y., et al. (2015). Effects of hand span size and right-left hand side on the piano playing performances: Exploration of the potential risk factors with regard to piano-related musculoskeletal disorders. *International Journal of Industrial Ergonomics*, *50*, 97–104. https://doi.org/10.1016/j.ergon.2015.09.011.
28. Lee, S. H. (2010). Hand biomechanics in skilled pianists playing a scale in thirds. *Medical Problems of Performing Artists*, *25*(4), 167. https://doi.org/10.21091/mppa.2010.4034.
29. Das, D., & Schultz, J. (2022). Principal component analysis of grasp force and pose during in-hand manipulation. *Journal of Medical and Biological Engineering, 42*(5), 658–670. https://doi.org/10.1007/s40846-022-00748-x
30. Zhang, S., et al. (2016). Muscle strength Assessment System using sEMG-Based force prediction method for wrist Joint. *Journal of Medical and Biological Engineering*, *36*(1), 121–131. https://doi.org/10.1007/s40846-016-0112-5.

31. Bergil, E., Oral, C., & Ergul, E. U. (2021). Efficient Hand Movement Detection using k-Means clustering and k-Nearest neighbor algorithms. *Journal of Medical and Biological Engineering*, *41*(1), 11–24. https://doi.org/10.1007/s40846-020-00537-4.
32. Chi, J. Y., et al. (2021). Interaction between hand span and different sizes of keyboards on EMG activity in pianists: An observational study. *Applied Ergonomics*, *97*, 103518. https://doi.org/10.1016/j.apergo.2021.103518.
33. Grieco, A., et al. (1989). Muscular effoert and musculo-skeletal disorders in piano students: Electromyographic, clinical and preventive aspects. *Ergonomics*, *32*(7), 697–716. https://doi.org/10.1080/00140138908966837.
34. Lai, C. J., et al. (2008). EMG changes during graded isometric exercise in pianists: Comparison with non-musicians. *Journal of the Chinese Medical Association*, *71*(11), 571–575. https://doi.org/10.1016/S1726-4901(08)70171-0.
35. Penn, I. W., et al. (1999). EMG power spectrum analysis of first dorsal interosseous muscle in pianists. *Medicine and Science in Sports and Exercise*, *31*(12), 1834–1838. https://doi.org/10.1097/00005768-199912000-00021.
36. Furuya, S., & Altenmüller, E. (2013). Flexibility of movement organization in piano performance. *Frontiers in Human Neuroscience*, *7*, 173. https://doi.org/10.3389/fnhum.2013.00173.
37. Harding, D. C., Brandt, K. D., & Hillberry, B. M. (1989). Minimization of finger joint forces and tendon tensions in pianists. *Medical Problems of Performing Artists*, *4*(3), 103–108.
38. Kinoshita, H., et al. (2007). Loudness control in pianists as exemplified in keystroke force measurements on different touches. *Journal of the Acoustical Society of America*, *121*(5), 2959. https://doi.org/10.1121/1.2717493.
39. Oku, T., & Furuya, S. (2017). Skilful force control in expert pianists. *Experimental Brain Research*, *235*(5), 1603–1615. https://doi.org/10.1007/s00221-017-4926-3.
40. Parlitz, D., Peschel, T., & Altenmuller, E. (1998). Assessment of dynamic finger forces in pianists: Effects of training and expertise. *Journal of Biomechanics*, *31*(11), 1063–1067. https://doi.org/10.1016/s0021-9290(98)00113-4.
41. MacRitchie, J. (2015). The art and science behind piano touch: A review connecting multi-disciplinary literature. *Musicae Scientiae*, *19*(2), 171–190. https://doi.org/10.1177/1029864915572813.
42. Fernandes, L. F. R. M., & de Barros, R. M. L. (2012). Grip pattern and finger coordination differences between pianists and non-pianists. *Journal of Electromyography and Kinesiology*, *22*(3), 412–418. https://doi.org/10.1016/j.jelekin.2012.02.007.