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Associations of Free-Living Physical Activity, Sleep, and Wellness with Neuromuscular, Postural, and Visuomotor Performance in University Students: A 14-Day Multimodal Study

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Abstract

Background and Objectives: Habitual physical activity, sleep, and psychological wellness may relate to physical and cognitive–motor performance in young adults, but these relationships are seldom examined within one free-living monitoring framework. This study examined associations of daily physical activity, sleep, and wellness with neuromuscular, postural, and visuomotor performance in university students. **Methods:** In a 14-day prospective observational design, Samsung Health provided daily step totals, while WHO-5, PSS-10, PSQI, and daily wellness measures characterized recovery. OptoJump, GYKO, and BlazePod assessments were repeated across three laboratory sessions. The prespecified analysis cohort comprised 242 students with ≥10 valid monitoring days (including ≥1 weekend day) and ≥2 valid laboratory sessions per outcome. Sex-adjusted linear mixed-effects models included 237 participants and 696 repeated observations, adjusting for session, age, BMI, weekly training volume, academic period, and testing time. **Results:** Each additional 1000 steps/day was associated with greater countermovement jump height ($\beta = 1.31$ cm, 95% CI 0.97–1.65), lower eyes-closed L5 movement velocity ($\beta = -0.65$ mm/s, 95% CI −1.00 to −0.30), and faster choice-response time ($\beta = -6.22$ ms, 95% CI −9.37 to −3.08; all Holm-adjusted $p < 0.001$). Higher perceived stress and poorer PSQI-defined sleep quality were independently associated with less favorable performance across all three domains, whereas mean self-reported sleep duration was not. **Conclusions:** Higher habitual step count, lower perceived stress, and better sleep quality were associated with a more favorable multidimensional performance profile. Because step count was summarized at the participant level, these findings should be interpreted as between-participant associations rather than causal or day-to-day readiness effects. Device-source attribution and postural-measure validation remain limitations.

Keywords: physical activity; sleep quality; perceived stress; countermovement jump; postural control; visuomotor response; university students; smartphone monitoring

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1. Introduction

Regular physical activity is a central determinant of health across the life course, with benefits spanning cardiovascular, metabolic, musculoskeletal, cognitive, and psychological domains. International guidance therefore emphasizes both accumulating moderate-to-vigorous physical activity and reducing sedentary behavior [1]. Evidence syntheses consistently show dose-responsive health advantages of greater physical activity, while longitudinal data support sustained benefits over time [2,3]. Despite this evidence, insufficient

physical activity remains common globally, including among young adults [4]. The university years are a particularly relevant period for studying lifestyle and multidimensional functional performance because students experience changes in daily structure, academic demands, sleep timing, stress, and exercise participation. Earlier work has documented substantial heterogeneity in physical activity among college students [5], while multinational and contemporary studies show that vigorous activity, sleep quality, stress, mental health, and quality of life are interrelated in this population [6,7]. University activity patterns can also change markedly in response to environmental and academic disruption [8], and recent studies link physical activity with sleep quality, psychological resilience, social adaptation, and perceived stress [9,10].

Wellness is multidimensional and should not be reduced to a single proprietary score. In the present study, psychological well-being, perceived stress, and sleep quality are therefore represented with established instruments. The WHO-5 is a brief measure with a strong international psychometric literature [11] and has also been evaluated in Romanian university students [12]. Perceived stress is assessed with the PSS-10, building on the original scale [13] and Romanian psychometric evaluation [14], while habitual sleep quality is assessed using the Pittsburgh Sleep Quality Index (PSQI) [15]. Daily step count offers an intuitive, scalable indicator of ambulatory physical activity and has been associated with important health outcomes in large cohorts [16]. Smartphone-based step monitoring is attractive for field research because it reduces participant burden and uses devices already carried in daily life. Validation work on Samsung S Health/Samsung Health and other smartphone or consumer activity systems indicates that step-count performance can be useful when device carriage, placement, synchronization, and valid-day rules are standardized [17–20]. At the same time, free-living validation studies highlight device heterogeneity and the need to distinguish relatively robust step measures from less reliable proprietary estimates such as energy expenditure [19–22].

Digital monitoring also enables repeated, ecologically valid assessment of day-to-day behavior. Smartphone-derived activity and sleep have been used to study well-being in free-living cohorts [23], and longitudinal in-the-wild work shows that sleep and behavioral patterns can covary with multidimensional cognitive performance [24]. Sleep loss is particularly relevant to physical and cognitive–motor performance because it can influence exercise, physiological, and cognitive responses [25], while meta-analytic evidence demonstrates measurable impairment across several cognitive domains after short-term sleep deprivation [26]. Neuromuscular performance provides a complementary objective domain. Countermovement jump (CMJ) height is widely used to characterize lower-limb explosive performance, and OptoJump photoelectric cells have demonstrated strong validity and reliability for estimating vertical jump height [27]. CMJ-derived measures have also been used to monitor neuromuscular status and acute fatigue [28,29]. The GYKO inertial sensor adds a portable inertial-measurement perspective and has published validity evidence for human performance assessment [30].

Postural control reflects the integration of visual, vestibular, somatosensory, and motor processes. Quiet-standing assessment is sensitive to task conditions such as visual input and repeated-trial structure [31,32], while sport and motor experience can shape postural strategies [33]. Portable inertial systems are increasingly used to quantify sway-related measures, and GYKO-based postural assessments have been applied in sports performance research [34]. For this reason, postural control is treated in the present study as a distinct functional domain rather than as a surrogate for jump performance. Visuomotor response is another component of multidimensional functional performance that cannot be inferred from step count or jump height alone. BlazePod has published test–retest evidence for visual–cognitive response-time assessment [35]. Related light-stimulus technologies have

shown that peripheral vision, manual lateralization, sports background, and training can influence simple- or choice-response-time performance [36–38]. More generally, response latency is shaped by both task and participant characteristics, reinforcing the need for standardized familiarization, stimulus rules, and response procedures [39].

Subjective wellness measures can complement objective performance testing because perceived fatigue, stress, sleep, soreness, and self-perceived readiness may capture aspects of recovery not represented by a single device metric. Systematic evidence from athlete monitoring research indicates that appropriately collected self-report measures can be sensitive to changes in training response [40], and classic monitoring frameworks likewise emphasize the value of repeated recovery-related observations [41]. Although the present cohort is composed of undergraduate physical education students rather than elite athletes, the same principle supports integrating standardized subjective and objective measures while avoiding causal or diagnostic interpretation.

Accordingly, the present study integrates 14 days of free-living Samsung Health step monitoring and daily wellness assessment with repeated laboratory measures of neuromuscular, postural, and visuomotor performance in undergraduate students. The primary objective is to determine whether habitual physical activity is associated with repeated indicators of multidimensional functional performance. A secondary objective is to examine whether psychological well-being, perceived stress, sleep quality, and self-reported sleep duration are independently associated with these performance domains after accounting for physical activity and relevant covariates. Because the primary activity exposure is each participant's mean step count across the monitoring period, the study is designed to estimate between-participant associations rather than acute day-to-day readiness effects.

2. Materials and Methods

2.1. Study Design, Setting, and Ethics

This prospective, 14-day repeated-measures observational study enrolled undergraduate students from the Faculty of Physical Education and Mountain Sports, Transilvania University of Brașov, Romania. Each participant contributed 14 consecutive days of free-living digital monitoring and three standardized laboratory assessments scheduled on Day 1, Day 8 $\pm$ 1 day, and Day 15 $\pm$ 1 day. The overall study period was 20 February–30 May 2026. The study protocol was approved by the Ethics Committee of the Faculty of Physical Education and Mountain Sports, Transilvania University of Brașov (approval No. 1124/20 February 2026) and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from each participant before any study-specific data were collected.

All objective assessments were conducted in the laboratory facilities of the Department of Physical Education and Special Motricity, Faculty of Physical Education and Mountain Sports, Transilvania University of Brașov. The same testing area, device configuration, and standardized sequence were used across repeated visits. No protocol amendments were made. Quality-control events and one mild transient adverse event were documented and handled according to the prespecified protocol, as detailed in Section 2.10.

2.2. Participants and Recruitment

The study database contained 283 screened/registered undergraduate students from the Faculty of Physical Education and Mountain Sports, Transilvania University of Brașov. Eligible students were invited to participate within the Faculty and received information about study procedures, voluntariness, confidentiality, and the right to withdraw before providing written informed consent. The prespecified primary analysis cohort required adequate digital monitoring and repeated laboratory data in addition to baseline eligibility.

The inclusion criteria were (1) current undergraduate enrollment at the Faculty of Physical Education and Mountain Sports; (2) age ≥ 18 years; (3) ability to understand the study procedures and provide written informed consent; (4) possession of a compatible Samsung smartphone on which Samsung Health could be installed and willingness to carry the smartphone on the body during waking activity throughout the 14-day monitoring period; (5) willingness and practical ability to attend the three scheduled laboratory assessments; and (6) ability to perform quiet standing, countermovement jumping, and the visuomotor response tasks safely. The enrollment exclusion criteria were (1) refusal or inability to provide written informed consent; (2) acute illness, current musculoskeletal injury/pain, or another medical contraindication that made maximal jumping, balance testing, or rapid-response tasks unsafe; (3) a neurological, vestibular, or other health condition judged to materially compromise safe completion or interpretation of the primary performance tests; and (4) inability to obtain usable Samsung Health step-count data using the study procedure. Analytic exclusions were defined separately and included failure to meet the prespecified digital-monitoring or laboratory-completeness thresholds.

Participant flow, exclusions, withdrawal status, and incomplete follow-up were documented in the study database. Missing observations were not replaced during data collection. Written informed consent was obtained before data collection for every participant included in the study.

2.3. Study Schedule and Repeated Measures

- Day 1: baseline demographic/anthropometric information, questionnaires, device profile/setup, and laboratory assessment.
- Days 1–14: Samsung Health monitoring and daily wellness records.
- Day 8 ± 1: second standardized laboratory assessment.
- Day 15 ± 1: final standardized laboratory assessment.

The same nominal schedule was applied throughout the study. Deviations from target visit days, when unavoidable, were retained in the database with the actual session date and days from enrollment; no undocumented protocol changes were permitted. The study schedule is summarized in Figure 1.

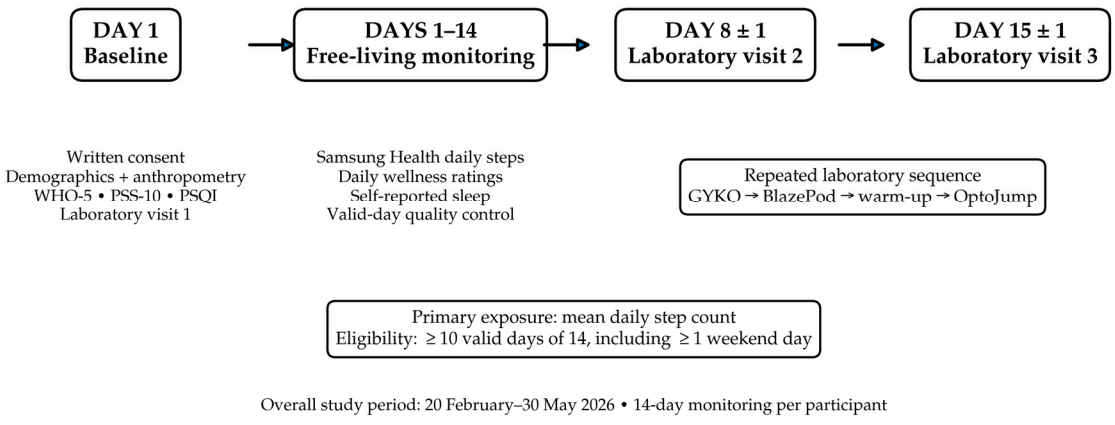

Figure 1. Overview of the 14-day study design, free-living monitoring period, and repeated laboratory assessment schedule.

2.4. Samsung Health Monitoring

Samsung Health was installed and configured on each participant's own Samsung smartphone at baseline and was used to characterize free-living physical activity. Daily step count was prespecified as the primary digital exposure. Participants were instructed to carry the smartphone on their person during waking activity, preferentially in a clothing pocket

or similarly body-carried position, and to avoid leaving the phone stationary during periods of locomotion. The device-profile record captured smartphone model, Android version, Samsung Health version, use of any paired wearable, and synchronization status. Samsung Health was installed on every participant's Samsung smartphone. The daily step total displayed in Samsung Health was entered into the study database under the participant's study identifier. Depending on the participant's device configuration, the Samsung Health step total could be sourced from the phone, a paired Galaxy Watch, or both; the device-profile source category was recorded. Daily source labels were also retained; discrepancies between the profile and day-level labels are considered in the source-sensitivity analyses. Device-profile categories therefore cannot be taken as verified day-level source assignments. At data checks, the collector verified that a step value was present, the app had synchronized without an unresolved error, and the participant confirmed carrying/wearing the relevant device for at least 10 waking hours on that day. This approach was informed by the smartphone and consumer-device validation literature emphasizing carriage behavior and explicit validity rules [17–22].

A monitoring day was considered valid when (1) a daily step-count value was present; (2) the participant confirmed carrying and/or wearing the phone or wearable source contributing to the displayed step total for at least 10 waking hours; and (3) no unresolved synchronization problem was present. The prespecified minimum for the primary activity analysis was ≥10 valid days out of 14, including ≥1 weekend day. The primary activity metric was the Samsung Health daily step count displayed on the participant's smartphone. Paired wearable use, when present, was documented but was not required for inclusion in the primary step-count analysis. Phone-only, watch-only, and combined device profiles were retained for source-sensitivity analyses. The recorded Samsung Health displayed daily total was analyzed; the original source-merging/deduplication procedure for combined profiles could not be independently reconstructed.

Samsung-derived sleep variables were treated as secondary because objective sleep availability depended on the presence of a compatible wearable. Objective sleep measures were therefore not included in the primary models reported here. Questionnaire-based sleep quality and daily self-reported sleep duration were available for the broader cohort.

2.5. Questionnaires and Daily Wellness

Psychological well-being was assessed with the Romanian WHO-5 Well-Being Index. The five items are scored 0–5, yielding a raw score of 0–25 and a percentage score of 0–100 after multiplication by four. Perceived stress was assessed with the Romanian PSS-10; items 4, 5, 7, and 8 are reverse scored, and the total score ranges from 0 to 40. Sleep quality was assessed with the authorized Romanian version of the Pittsburgh Sleep Quality Index (PSQI), producing seven component scores (0–3) and a global score of 0–21. Under the conventional PSQI screening threshold, global scores >5 indicate poor sleep quality [15]. The full copyrighted PSQI wording is not reproduced in the study database or manuscript. The WHO-5 refers to the preceding two weeks, whereas the PSS-10 and PSQI assess the preceding month. The instruments and Romanian psychometric sources are cited in [11–15]. The WHO-5 refers to the preceding two weeks, whereas the PSS-10 and PSQI refer to the preceding month.

The Romanian WHO-5 version has published psychometric evidence from Romanian university students [11,12], and the Romanian PSS-10 has demonstrated adequate internal consistency and test–retest reliability in an undergraduate sample [13,14]. The PSQI was administered using the authorized Romanian form retained with the approved study materials and scored according to the original instrument rules [15]. Daily wellness was recorded on 1–7 scales for sleep quality (1 = very poor, 7 = excellent), fatigue (1 = none,

7 = extreme), stress (1 = none, 7 = extreme), muscle soreness (1 = none, 7 = extreme), and perceived readiness (1 = very poor, 7 = excellent). Participants additionally reported sleep duration, illness symptoms, and unusual physical activity.

2.6. Laboratory Standardization and Pre-Test Controls

At each laboratory visit, collectors recorded the session date and time, academic period, ambient temperature, caffeine consumption during the previous 3 h, vigorous exercise during the previous 24 h, alcohol consumption during the previous 24 h, previous-night sleep duration, acute illness, current pain or injury, and pain intensity. When feasible, the same participant was tested at a similar time of day across visits. Identical clock times were not required for every participant or visit; the recorded testing time was included in the adjusted models. The standardized assessment sequence was GYKO postural control, BlazePod visuomotor testing, standardized lower-limb warm-up, and OptoJump countermovement jumping.

Postural and visuomotor assessments were completed before maximal jumping to minimize the influence of acute exertion on sway and response performance. The lower-limb warm-up preceding OptoJump consisted of approximately 5 min of light self-paced locomotion, dynamic lower-limb mobility movements, and two progressive familiarization countermovement jumps. Participants wore comfortable sports clothing and indoor athletic footwear for dynamic tasks. A minimum of approximately 2 min separated device blocks, with longer recovery provided when necessary to restore comfortable breathing and readiness. Caffeine intake, recent vigorous exercise, alcohol intake, previous-night sleep duration, illness, and pain were recorded rather than used as post-enrollment exclusion criteria unless a safety concern precluded testing. Participants were not tested when acute illness, injury, or another safety concern made performance testing inappropriate; such sessions were retained in the database as missed or ineligible rather than deleted. The same test order, device settings, trial structure, and environmental arrangement were maintained across sessions. Any unavoidable departure from the standardized procedure was recorded in the protocol-deviation field and retained for sensitivity analyses.

2.7. Neuromuscular Performance: OptoJump Countermovement Jump

Lower-limb explosive performance was assessed using OptoJump Next (Microgate S.r.l., Bolzano, Italy; software v1.13.2; device serial OJ-2024-8841). Following the standardized warm-up, participants performed three recorded bilateral countermovement jumps. They began from an upright stance with feet in a comfortable self-selected position, kept both hands on the hips throughout the movement, performed a rapid self-selected countermovement, and jumped vertically with maximal effort. Participants were instructed to maintain extended lower limbs during the flight phase and to land in a controlled manner within the measurement area.

Two progressive familiarization jumps were completed during the warm-up before recorded trials. Approximately 60 s of passive recovery was provided between recorded CMJ attempts. A trial was considered invalid when the hands left the hips, the participant visibly altered the prescribed technique, the participant landed outside the measurement area, or a device/measurement error occurred; invalid trials were flagged with the reason and were not silently deleted. Jump height (cm) and flight time (s) were recorded directly from the OptoJump software. Three valid recorded trials were targeted at each session; the measurement settings and the hands-on-hips technique were kept constant across the three visits. The choice of OptoJump and CMJ height was supported by the published validity and neuromuscular-monitoring literature [27–29]. The primary OptoJump outcome is session-level mean CMJ height across valid recorded trials. Maximum CMJ height and

flight time are secondary outcomes. A session-level CMJ value requires at least one valid recorded jump. When multiple jumps are valid, their mean is used; when only one jump is valid, its height constitutes the session-level value. Sessions without any valid recorded jump are treated as missing for the primary CMJ analysis.

2.8. Postural Control: GYKO

Postural control was assessed using the GYKO inertial sensor system (Microgate S.r.l., Bolzano, Italy; software/firmware v2.4.1; device serial GYKO-TR-5521). The sensor was secured at the lower trunk/L5 region using the same fixation method at every visit. Participants completed two 30 s eyes-open trials followed by two 30 s eyes-closed trials while standing quietly on the same firm, level surface. Portable inertial assessment and postural-control methods were interpreted in the context of the published GYKO and quiet-standing literature [30–34]. Participants adopted a comfortable bipedal stance with the feet approximately hip-width apart and parallel, arms relaxed alongside the body, and the same foot position reproduced using floor markings at repeated visits. For eyes-open trials, participants fixated a stationary target positioned at approximately eye level about 2 m in front of them; for eyes-closed trials, they were instructed to close their eyes after assuming the same stance and remain as still as possible. Approximately 30 s of seated or quiet-standing rest was provided between balance trials. Trials were repeated only when a clear protocol violation or device error occurred, and the original attempt remained documented as invalid.

The primary GYKO outcome is mean lower-trunk movement velocity (the GYKO sway-velocity output) averaged across valid eyes-closed trials at each session. Eyes-open mean sway velocity, sway path, sway area, anterior–posterior range, and medio-lateral range are secondary outcomes. A condition-level value requires at least one valid trial, with the mean of two valid trials used when both are available. As a sensor-mounted measure at L5, the reported velocity (mm/s) characterizes lower-trunk movement, not force-platform center-of-pressure displacement or velocity.

2.9. Visuomotor Performance: BlazePod

Visuomotor response performance was assessed with a four-pod BlazePod system (Play Coyotta Ltd., Tel Aviv, Israel; app v4.12.3; set ID BP-SET-07) using the locked configuration ID CFG-SIMPLE-CHOICE-4POD-STD-v1. Two tasks were administered in a fixed order: a 30 s simple-response task and a 45 s choice-response task. For each task, participants completed one familiarization trial followed by three recorded trials. This structure was informed by reliability work on BlazePod and related light-stimulus response-time paradigms [35–39]. The four pods were arranged symmetrically on a marked horizontal testing surface within comfortable reach of the participant and were returned to the same marked positions at every session. Participants stood at the same marked starting position and responded using the dominant hand. At the start of each trial, the response hand was placed at the designated central start marker. For the simple-response condition, participants touched the illuminated pod as rapidly as possible according to the single-response rule. For the choice-response condition, illumination was presented pseudo-randomly across the four pods and participants were required to identify and touch the active pod as quickly and accurately as possible. Exact inter-pod spacing, stimulus timing (including inter-stimulus intervals), and response-hand repositioning between successive stimuli were not specified in the available protocol description.

Participants were instructed to prioritize both speed and accuracy. The same dominant-hand rule, pod arrangement, start position, stimulus rules, and task order were maintained across visits. Approximately 30 s of rest was provided between trials and 60 s between task

conditions. Mean response time (ms), hits, misses/errors, trial validity, app version, and device/set identifier were recorded directly from the BlazePod application. Detailed app rules for missed or incorrect responses were not available in the supplied documentation.

The primary BlazePod outcome is the session-level mean response time for the choice-response task, averaged across the available valid recorded trials. A session requires at least one valid recorded choice-response trial; when only one trial is valid, its response time is used as the session-level value. Mean response time is used rather than median response time because the app-derived mean is available consistently across the study database, whereas median response time is available only when a raw-response export exists. Simple-response mean time, hits, and errors are secondary outcomes.

2.10. Data Quality, Missing Data, and Protocol Deviations

Raw records were preserved unchanged. Derived variables, exclusions, and recoding decisions were generated in a separate analysis dataset with a reproducible change log. Trial-level validity flags, day-level validity flags, source verification, protocol-deviation logs, and adverse-event fields were reviewed during quality control. The QC strategy also reflects broader recommendations from the free-living wearable and smartphone validation literature [17–22]. For analyses using Samsung Health step counts, participants must contribute ≥10 valid days of the 14-day monitoring period, including ≥1 weekend day. Days failing the wear/carry, synchronization, or step-presence rule are excluded from step summaries but remain in the raw database.

Primary repeated-measures analyses required at least two laboratory sessions with a valid outcome for the relevant performance domain. Individual invalid trials were excluded from session aggregation but retained in the raw database with the reason recorded. No single-value imputation was used to replace invalid device trials. No protocol amendments were made. Six study events/deviations were logged in the quality-control record, including device/synchronization issues, one delayed laboratory visit, two days of smartphone non-adherence, and one mild adverse event (transient dizziness during an eyes-closed GYKO trial). The affected GYKO trial was stopped, the participant rested for 10 min, and no further symptoms were reported. Invalid or affected records were handled according to the prespecified quality-control rules.

2.11. Outcomes and Statistical Analysis

The prespecified primary exposure is mean daily step count across valid Samsung Health monitoring days, analyzed continuously and reported per 1000 steps/day. The three primary performance outcomes are (1) session mean OptoJump CMJ height; (2) session mean GYKO eyes-closed L5 movement velocity; and (3) session mean BlazePod choice-response time. Primary repeated-measures analyses require at least two laboratory sessions with a valid outcome for the relevant performance domain. Because mean step count is summarized once per participant across the 14-day monitoring period, its regression coefficient primarily represents a between-participant association with repeated performance outcomes rather than a within-participant day-to-day effect.

Primary associations are estimated with linear mixed-effects models including participant-specific random intercepts and fixed effects for session. The adjusted model includes age, sex, BMI, weekly training volume, academic period, and laboratory testing time. Because only five participants selected sex categories other than male or female, these participants are retained in descriptive analyses but omitted from sex-adjusted mixed-effects models to avoid unstable estimates from sparse categories. Weekly training volume was entered as participant-level self-reported hours/week; whether compulsory practical classes were included was not separately recorded. Academic period was entered as a session-level

categorical indicator (teaching period as reference; the spring category was verified against the study calendar) and testing time as the session-level clock hour. These covariates were used to address between-participant training exposure and calendar/time-of-day variation. Secondary multivariable models add mean self-reported sleep duration, WHO-5 well-being, PSS-10 perceived stress, and PSQI global sleep-quality score to evaluate their independent associations with each primary outcome. Statistical analyses were performed using IBM SPSS Statistics, version 26 (IBM Corp., Armonk, NY, USA). In compact notation, the primary model was outcome ~ mean steps/1000 + session + age + sex + BMI + weekly training volume + academic period + testing time + (1|participant). The session-specific laboratory clock time and academic period were recorded at each visit; mean steps and baseline questionnaire scores were participant-level measures. The adjusted model is $Y_{ij} = \beta_0 + \beta_1(\text{steps}_i/1000) + \beta_2(\text{session}_j) + \beta_3(\text{age}_i) + \beta_4(\text{sex}_i) + \beta_5(\text{BMI}_i) + \beta_6(\text{training hours}_i) + \beta_7(\text{academic period}_{ij}) + \beta_8(\text{testing hour}_{ij}) + u_i + \varepsilon_{ij}$; secondary models additionally include the four wellness variables.

All primary estimates are reported with 95% confidence intervals. The family of three primary step-count/performance tests is controlled using the Holm sequential procedure at a two-sided family-wise $\alpha = 0.05$ [42]. The Benjamini–Hochberg false-discovery-rate correction was applied to the 12 secondary wellness–outcome tests (WHO-5, PSS-10, PSQI, and self-reported sleep duration across three outcomes); the resulting adjusted values are denoted q [43]. Analyses were originally conducted in IBM SPSS Statistics, version 26. For independent post-review verification, random-intercept models were re-estimated by restricted maximum likelihood with two-sided Wald-z inference and 95% Wald confidence intervals. The original SPSS v.26 model specifications, estimation procedures, confidence intervals, and significance tests were checked by the authors and confirmed as consistent with the reported results. Missing repeated outcomes are not single-value imputed; mixed models use available valid observations under their likelihood assumptions. Sensitivity analyses additionally adjust for the documented Samsung Health primary data source and restrict the cohort to participants with completed study status.

2.12. Generative AI Assistance

During preparation of this manuscript and study, the authors used ChatGPT (OpenAI; GPT-5.6 Sol) to assist with study-structure organization, statistical coding and analysis, manuscript drafting, and language refinement. All outputs were reviewed and verified by the authors, who retained full responsibility for the analyses, interpretation, and final content.

3. Results

A total of 283 participant records were present in the study database. Of these, 255 met the digital-monitoring criterion and 242 also fulfilled the repeated-laboratory requirements; 28 did not meet the monitoring inclusion requirements (17 records labeled Excluded and 11 Screened), and 13 additional records did not meet the repeated-laboratory requirement (12 Withdrawn and one Completed record with only one valid session). The prespecified primary analysis cohort comprised 242 participants who provided written consent, completed baseline/questionnaire assessment, contributed ≥10 valid Samsung Health days including ≥1 weekend day, and had at least two valid laboratory sessions for each primary performance domain.

3.1. Participant Flow and Data Completeness

The 242 participants in the primary analysis cohort included 214 with completed study status and 28 who remained coded as administratively enrolled at database lock despite

meeting the prespecified analysis criteria. Study-status coding did not determine analytic eligibility; all 28 met the same predefined inclusion thresholds, although the administrative reason for their unclosed status was not documented. Restriction to Completed status and sex categories represented in the adjusted models resulted in 209 participants (613 observations). Across the three sessions, 238, 236, and 237 valid primary laboratory observations were available, respectively. Five participants selected sex categories other than male/female and were retained in descriptive analyses; the sex-adjusted mixed-effects models therefore included 237 participants and 696 repeated observations. Participant flow and analysis-set construction are detailed in Supplementary Figure S1.

3.2. Participant Characteristics

The baseline characteristics of the primary analysis cohort are summarized in Table 1. The cohort consisted predominantly of young adults with normal-range mean body mass index and a balanced sex distribution. A total of 156 of the 242 students (64.5%) had PSQI > 5, consistent with poor sleep quality according to the conventional screening cut-off.

Table 1. Baseline characteristics of the primary analysis cohort.

Characteristic	Value
Participants, n	242
Age, years	20.88 ± 1.57
Female, n (%)	124 (51.2)
Male, n (%)	113 (46.7)
Other/prefer not to say, n (%)	5 (2.1)
Height, cm	171.22 ± 8.55
Body mass, kg	67.19 ± 12.32
BMI, kg/m^2	22.86 ± 3.45
WHO-5, 0–100	62.99 ± 21.38
PSS-10, 0–40	15.98 ± 8.10
PSQI global score, 0–21	7.43 ± 4.36

3.3. Free-Living Activity, Sleep, and Wellness

The analysis cohort showed high compliance with the free-living monitoring protocol. Participants contributed 13.05 ± 0.92 valid Samsung Health days on average and 3.71 ± 0.51 valid weekend days. Mean daily step count was 9896 ± 2825 steps/day, and mean self-reported sleep duration was 7.07 ± 0.66 h/night. Activity, sleep, and wellness characteristics are summarized in Table 2. Device-profile categories were phone-only in 43 participants, watch-only in 110, and combined in 89; these profile categories did not always agree with individual daily source labels.

Table 2. Free-living activity, sleep, wellness, and data-completeness characteristics.

Monitoring/WELLNESS Variable	Value
Valid Samsung Health days, n	13.05 ± 0.92
Weekend valid days, n	3.71 ± 0.51
Mean daily step count	9896.47 ± 2825.16

Table 2. *Cont.*

Monitoring/WELLNESS Variable	Value
Mean daily active time, min	120.00 ± 34.51
Self-reported sleep duration, h	7.07 ± 0.66
Sleep quality, 1–7	4.07 ± 1.15
Fatigue, 1–7	3.53 ± 1.10
Stress, 1–7	3.28 ± 1.06
Muscle soreness, 1–7	3.24 ± 0.73
Perceived readiness, 1–7	4.74 ± 1.40
Participants with 3 valid sessions per device, n (%)	227 (93.8)

3.4. Neuromuscular, Postural, and Visuomotor Outcomes

Outcome values were generally stable across the three laboratory sessions, with only small between-session differences in the sample means. The session-specific descriptive statistics for OptoJump, GYKO, and BlazePod are presented in Table 3. Across the valid recorded choice-response trials in the descriptive cohort, the BlazePod records contained 27,131 hits and 2147 misses/errors (approximately 7.3% of recorded responses classified as misses/errors).

Table 3. Session-specific descriptive statistics for the laboratory outcomes.

Session	n	CMJ Height (cm)	GYKO EO L5 vel. (mm/s)	GYKO EC L5 vel. (mm/s)	BlazePod Simple RT (ms)	BlazePod Choice RT (ms)
1	238	35.70 ± 9.70	14.58 ± 5.26	19.98 ± 7.48	285.83 ± 63.34	390.45 ± 66.00
2	236	35.40 ± 9.59	14.54 ± 5.32	20.10 ± 7.30	285.77 ± 61.98	390.45 ± 64.84
3	237	35.59 ± 9.58	14.51 ± 5.48	20.01 ± 7.52	285.31 ± 62.07	390.66 ± 65.98

3.5. Mixed-Effects Models

In the primary mixed-effects analyses adjusted for session, age, BMI, weekly training volume, sex, academic period, and laboratory testing time, higher mean daily step count was independently associated with all three primary outcomes. Per additional 1000 steps/day, CMJ height was 1.31 cm greater (95% CI 0.97–1.65, $p < 0.001$), GYKO eyes-closed L5 movement velocity was 0.65 mm/s lower (95% CI −1.00 to −0.30, $p < 0.001$), and BlazePod choice-response time was 6.22 ms shorter (95% CI −9.37 to −3.08, $p < 0.001$). All three associations remained significant after Holm correction (Table 4).

Table 4. Primary mixed-effects models for the association between mean daily step count and the three primary outcomes.

Outcome	Observations	Participants	β Per 1000 Steps/Day	95% CI	*p*-Value
CMJ height (cm)	696	237	1.31	0.97 to 1.65	<0.001
GYKO eyes-closed L5 velocity (mm/s)	696	237	−0.65	−1.00 to −0.30	<0.001
BlazePod choice-response time (ms)	696	237	−6.22	−9.37 to −3.08	<0.001

In secondary multivariable models, the step-count associations remained robust. The complete secondary fixed-effect estimates, sample sizes, 95% confidence intervals, raw *p*-values, and Benjamini–Hochberg-adjusted q-values for the 12 wellness tests are shown in Table 5. Higher PSS-10 scores were associated with lower CMJ height ($\beta = -0.22$ cm per point, $p < 0.001$), greater eyes-closed L5 movement velocity ($\beta = 0.33$ mm/s per point, $p < 0.001$), and slower choice-response time ($\beta = 3.11$ ms per point, $p < 0.001$). Higher PSQI scores showed the same unfavorable pattern across all three outcomes (CMJ: $\beta = -0.36$ cm, $p = 0.002$; L5 movement velocity: $\beta = 0.39$ mm/s, $p < 0.001$; choice-response time: $\beta = 3.35$ ms, $p < 0.001$). Higher WHO-5 scores were independently associated with lower L5 movement velocity and faster choice-response time but not with CMJ height after full adjustment. Mean self-reported sleep duration was not independently associated with any primary outcome (all $p > 0.44$). Sensitivity analyses restricted to participants with completed study status showed similar step-count associations (CMJ height: $\beta = 1.35$ cm per 1000 steps/day, 95% CI 0.99–1.72, $p < 0.001$; GYKO eyes-closed L5 movement velocity: $\beta = -0.69$ mm/s, 95% CI −1.06 to −0.32, $p < 0.001$; BlazePod choice-response time: $\beta = -5.77$ ms, 95% CI −9.15 to −2.39, $p < 0.001$). Additional adjustment for Samsung Health primary data source did not materially alter the direction or magnitude of the associations. Given the mismatch between device profiles and daily source labels, this sensitivity analysis does not establish phone–watch measurement equivalence. In exploratory nested-model comparisons using maximum likelihood, adding all four wellness variables improved within-sample model fit (CMJ: likelihood-ratio $\chi^2(4) = 80.35$; GYKO: 149.41; BlazePod: 154.18; all $p < 0.001$) without implying improved out-of-sample prediction.

Table 5. Complete secondary random-intercept mixed-effects models (237 participants and 696 observations for each outcome).

Outcome	Fixed Effect	β	95% CI	*p* (Raw)	q (BH)
CMJ	Intercept	17.179	0.110 to 34.249	0.049	—
	Steps (per 1000/day)	1.493	1.187 to 1.799	<0.001	—
	Age (years)	−0.093	−0.571 to 0.386	0.705	—
	Sex (coded 0/1)	11.376	9.847 to 12.905	<0.001	—
	BMI (kg/m^2)	0.111	−0.111 to 0.333	0.326	—
	Training (h/week)	−0.157	−0.395 to 0.082	0.198	—
	Academic period: non-teaching	−0.182	−0.752 to 0.387	0.530	—
	Academic period: spring	−1.544	−4.766 to 1.677	0.347	—
	Laboratory session 2	−0.115	−0.401 to 0.172	0.433	—
	Laboratory session 3	−0.160	−0.461 to 0.141	0.297	—
	Testing time (clock hour)	0.001	−0.053 to 0.055	0.972	—
	Mean sleep duration (h)	0.330	−1.089 to 1.749	0.649	0.708
	WHO-5 (0–100)	0.037	−0.008 to 0.081	0.104	0.139
	PSS-10 (0–40)	−0.217	−0.339 to −0.095	<0.001	0.001
	PSQI (0–21)	−0.364	−0.597 to −0.132	0.002	0.004
GYKO EC (L5)	Intercept	25.976	10.856 to 41.095	<0.001	—
	Steps (per 1000/day)	−0.836	−1.107 to −0.566	<0.001	—
	Age (years)	−0.101	−0.524 to 0.322	0.640	—

Table 5. *Cont.*

Outcome	Fixed Effect	β	95% CI	*p* (Raw)	q (BH)
	Sex (coded 0/1)	−4.934	−6.288 to −3.581	<0.001	—
	BMI (kg/m^2)	−0.045	−0.241 to 0.152	0.656	—
	Training (h/week)	0.155	−0.056 to 0.366	0.150	—
	Academic period: non-teaching	0.481	−0.157 to 1.119	0.140	—
	Academic period: spring	−1.281	−4.730 to 2.169	0.467	—
	Laboratory session 2	0.030	−0.304 to 0.365	0.858	—
	Laboratory session 3	0.080	−0.270 to 0.430	0.654	—
	Testing time (clock hour)	−0.010	−0.072 to 0.052	0.754	—
	Mean sleep duration (h)	0.480	−0.776 to 1.736	0.454	0.544
	WHO-5 (0–100)	−0.068	−0.108 to −0.029	<0.001	0.001
	PSS-10 (0–40)	0.329	0.221 to 0.437	<0.001	<0.001
	PSQI (0–21)	0.389	0.183 to 0.594	<0.001	<0.001
BlazePod choice	Intercept	479.558	345.307 to 613.808	<0.001	—
	Steps (per 1000/day)	−7.974	−10.378 to −5.570	<0.001	—
	Age (years)	−1.599	−5.357 to 2.159	0.404	—
	Sex (coded 0/1)	−31.439	−43.452 to −19.426	<0.001	—
	BMI (kg/m^2)	−0.589	−2.331 to 1.152	0.507	—
	Training (h/week)	1.263	−0.612 to 3.138	0.187	—
	Academic period: non-teaching	−1.715	−7.650 to 4.220	0.571	—
	Academic period: spring	3.809	−27.904 to 35.522	0.814	—
	Laboratory session 2	−0.733	−3.877 to 2.411	0.648	—
	Laboratory session 3	2.192	−1.099 to 5.482	0.192	—
	Testing time (clock hour)	−0.145	−0.731 to 0.442	0.629	—
	Mean sleep duration (h)	1.108	−10.038 to 12.255	0.845	0.845
	WHO-5 (0–100)	−0.534	−0.882 to −0.186	0.003	0.004
	PSS-10 (0–40)	3.112	2.153 to 4.072	<0.001	<0.001
	PSQI (0–21)	3.346	1.518 to 5.173	<0.001	<0.001

Table 5 note. Independent reanalysis using REML/Wald-z; all models adjusted for the listed terms. GYKO EC denotes L5-derived lower-trunk movement velocity, not center-of-pressure displacement. The academic-period category "spring" was verified against the study calendar and SPSS records; correcting the label did not affect the model estimates. q-values use the Benjamini–Hochberg procedure for the 12 wellness tests only; dashes indicate terms outside this correction family. The original SPSS v.26 output and inferential results were confirmed by the authors.

4. Discussion

The principal finding of this study was that higher habitual free-living physical activity, indexed by the Samsung Health daily step count, was consistently associated with a more favorable multidimensional performance profile. In adjusted mixed-effects models, each additional 1000 steps/day was associated with approximately 1.31 cm greater countermovement jump height, 0.65 mm/s lower L5 movement velocity during eyes-closed standing, and a 6.22 ms faster BlazePod choice-response time. These associations remained statistically significant after multiplicity control and were directionally stable in completed-status and device-profile sensitivity analyses. Because step count was averaged across the monitoring period for each participant, these coefficients should be interpreted as between-

participant associations; they do not imply that increasing an individual student's daily steps by 1000 would cause the corresponding change in performance. The neuromuscular findings are coherent with the broader literature linking habitual physical activity and physical fitness and with the use of the countermovement jump as an accessible performance-monitoring marker [1–5,27–29]. In the present cohort, participants with higher step counts demonstrated superior CMJ performance, suggesting that a simple ambulatory exposure metric derived from a smartphone may reflect meaningful differences in lower-limb functional capacity. Although step count is not a direct measure of training load or intensity, it likely captures part of the total locomotor activity exposure in university life.

The postural-control findings extend the study beyond conventional activity–fitness analyses. Lower L5 movement velocity during eyes-closed standing among more active participants is compatible with a trunk-movement association but cannot itself demonstrate better center-of-pressure control or sensorimotor integration [31–34]. The eyes-closed condition removes visual input, but criterion validation of this specific L5 protocol is needed before stronger balance-related inferences can be made. The visuomotor results are also noteworthy. The faster choice-response time in students with higher step counts and better wellness profiles is compatible with evidence that sleep, behavioral patterns, and physical activity are linked with cognitive–motor performance [23–26,35–39]. The present results therefore support the concept of multidimensional functional performance in young adults and show that a low-cost monitoring strategy can identify associations across both physical and visuomotor domains. A recent virtual-reality study compared visual attention and response time in athletes and non-athletes [44], providing a relevant but task-specific context for the present visuomotor association. Differences in the study populations and testing paradigms preclude direct comparison of effect sizes or causal interpretation.

Wellness measures were associated with performance after adjustment for step count. Higher perceived stress and poorer PSQI-defined sleep quality were independently associated with less favorable performance across all three primary domains, while higher WHO-5 well-being was associated with better postural and visuomotor outcomes. In contrast, mean self-reported sleep duration was not independently associated with performance after multivariable adjustment. The cohort mean PSQI score was 7.43, and 156 of the 242 participants (64.5%) scored >5, indicating that poor self-reported sleep quality was common in this sample. Similarly, steps/day and the app-derived active-time summary do not allow classification against the WHO moderate-to-vigorous physical activity recommendations. This pattern suggests that qualitative and psychological dimensions of recovery may be more informative than average sleep duration alone in this student population. Several strengths should also be emphasized, including the 14-day free-living monitoring period, repeated objective laboratory assessments, the explicit quality-control framework, the pragmatic Samsung Health monitoring strategy, and integration of neuromuscular, postural, and visuomotor outcomes within a single design.

The study also has limitations. The observational design does not support causal inference, smartphone step counts depend on participants carrying the device during waking activity [17–22], and the sample was drawn from a single faculty with a strong physical-activity orientation, which may limit generalizability. Residual confounding by baseline fitness, sport specialization, training history, or other unmeasured characteristics also remains possible; students who are generally fitter may both accumulate more steps and perform better across the laboratory tasks. Moreover, because mean step count is a participant-level exposure, the mixed-effects models account for repeated outcomes but do not identify the within-person effects of day-to-day changes in activity. The full 14-day step average includes days following the first and second laboratory visits, whereas the baseline questionnaires capture partly different retrospective periods; therefore, temporal

precedence of activity and sleep relative to performance cannot be demonstrated. Objective sleep measures were not uniformly available because the primary monitoring strategy was smartphone-based rather than watch-based. The GYKO outcome was derived from lower-trunk inertial sensing rather than a force platform; device-specific sway processing and criterion validity and reliability for this exact L5 quiet-standing protocol require further documentation. Aggregate BlazePod errors are provided, but the available summaries do not permit a formal participant-level analysis of speed–accuracy trade-offs. Unreported pod spacing, stimulus timing, and response/repositioning rules further constrain reproducibility of the exact protocol. Device profiles did not always agree with daily source labels, and combined phone/watch totals could not be independently disentangled or deduplicated; source-adjusted analyses therefore cannot demonstrate measurement consistency across devices. Exploratory quadratic checks suggested possible departures from linear step-count associations. In addition, although the core analysis cohort included all participants with analyzable data, 28 participants remained coded as administratively enrolled at database lock and the sex-adjusted models excluded five participants with sparse sex categories. Future studies using time-varying activity and recovery exposures, lagged analyses, and more direct measures of training load and fitness would help distinguish habitual between-person differences from acute within-person changes. From an applied perspective, daily step count should not be interpreted as a surrogate for performance, but when combined with brief wellness and sleep-quality measures, it may provide useful complementary information across several functional domains.

5. Conclusions

In undergraduate students from the Faculty of Physical Education and Mountain Sports, higher free-living daily step counts were associated with greater countermovement jump performance, lower L5 movement velocity during eyes-closed standing, and a faster visuomotor response time. Lower perceived stress and better PSQI-defined sleep quality were also independently associated with a more favorable multidimensional performance profile, while mean self-reported sleep duration was not independently associated with the primary outcomes. Because the activity exposure was summarized at the participant level, the findings describe between-participant associations and should not be interpreted as causal or as evidence of acute day-to-day readiness effects. Samsung Health step monitoring, brief wellness measures, and accessible sensor-based testing may offer complementary descriptive information on functional performance, subject to device-source and protocol-validation limitations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jfmk11040457/s1, Supplementary Methods S1: Study Design, Population, and Ethics; Supplementary Methods S2: Samsung Health Free-Living Monitoring; Supplementary Methods S3: Questionnaires and Daily Wellness; Supplementary Methods S4: Laboratory Testing; Supplementary Methods S5: Analysis-Set Construction and Quality Control; Figure S1: Participant flow and construction of the primary analysis cohort; Table S1: Laboratory systems, measurement domains, and primary outcomes; Table S2: Study schedule and measurement domains; Table S3: Operational definitions of key analysis variables; Table S4: Data completeness and monitoring compliance in the current analysis dataset; Table S5: Sensitivity analyses for the primary step-count associations.

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Informed Consent Statement: Written informed consent was obtained from all subjects involved in the study before data collection.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request. The participant-level dataset is not publicly available because it contains coded human-participant data subject to ethical and privacy restrictions.

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Abbreviations

The following abbreviations are used in this manuscript:

CMJ	Countermovement jump
GYKO	Inertial measurement system used for postural-control assessment
PSS-10	10-item Perceived Stress Scale
PSQ	Pittsburgh Sleep Quality Index
RT	Response time
WHO-5	World Health Organization-Five Well-Being Index
FDR	False discovery rate
LMM	Linear mixed-effects model

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