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Research Article

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Development and Validation of a s Standardized Video-Based Assessment of Movement Quality in Breast Cancer Survivors

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ABSTRACT

Objective: To develop and validate a standardized, video-based movement quality assessment for breast cancer survivors, termed the Rehabilitation Movement Assessment Protocol (ReMAP) by examining its construct validity and internal reliability.

Design: Cross-sectional validation study.

Setting: Outpatient rehabilitation settings.

Participants: Seventy breast cancer survivors able to ambulate independently.

Methods: Seventy breast cancer survivors completed the movement quality assessment at baseline, consisting of sequential, unfamiliar functional tasks designed to emphasize real-time sensorimotor control. Movement quality metrics-including postural stability (mediolateral center-of-mass sway), coordination (lateral correction rate, movement smoothness), movement efficiency (energy ratio), and motor control (trajectory variability)-were derived from RGB video using pose estimation. Construct validity was evaluated by examining Pearson and Spearman correlations between kinematic metrics and clinical reference measure, including the Timed Up and Go test. Within-session internal reliability was assessed using intraclass correlation coefficients (ICC [3,1]) across repeated task segments. Measurement error indices, including standard error of measurement and minimal detectable change at the 95% confidence level, were calculated.

Results: Movement quality metrics demonstrated substantial inter-individual variability without floor or ceiling effects. Associations with clinical reference measures were generally weak, supporting the conceptual distinction between movement quality and performance-based outcomes. Coordination-related correction behavior showed a significant monotonic association with Timed Up and Go performance (Spearman $\rho = 0.295$, $p = 0.015$). Internal reliability varied across domains, with excellent reliability for coordination, good reliability for motor control, moderate reliability for movement efficiency and smoothness, and lower reliability for postural sway. Measurement error indices provided interpretable thresholds for measurement precision.

Conclusion: The ReMAP Assessment provides a feasible and objective approach to quantifying movement quality in breast cancer survivors. Demonstrating acceptable construct validity and domain-specific internal reliability, this assessment captures qualitative aspects of movement behavior that are not reflected by conventional performance-based mobility tests and may enhance functional assessment in oncology rehabilitation.

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Abbreviations

COM	:	Center-of-mass
ICC	:	Intraclass correlation coefficients
MDC_{95}	:	Minimal detectable change at the 95% confidence level
ReMAP	:	Rehabilitation Movement Assessment Protocol
SEM	:	Standard error of measurement
TUG	:	Timed Up and Go

Keywords: Cancer Survivors, Movement Quality, Functional Mobility, Postural Balance, Motion Analysis, Measurement properties

Introduction

Breast cancer survivors commonly experience persistent impairments in balance, coordination, and movement efficiency that affect daily function and independence [1]. These difficulties are frequently reported even among individuals with preserved muscle strength and aerobic capacity, indicating functional limitations that are not adequately explained by conventional assessments of physical capacity [2,3]. Such impairments are clinically consequential, as they are associated with increased fall risk, activity restriction, and long-term disability in cancer survivorship [4,5]. However, commonly used performance-based measures of functional mobility primarily quantify task completion time or distance and provide limited information about how movements are controlled and executed. As a result, qualitative deficits in movement control that are characteristic of treatment-related functional impairment in cancer survivors may remain undetected [6].

Movement quality refers to qualitative characteristics of motor behavior, including postural stability, inter-limb coordination, and movement efficiency during task performance. These attributes reflect underlying sensorimotor control strategies rather than physical capacity alone. In cancer survivorship, functional impairment often arises not from focal neurological injury or generalized age-related decline, but from treatment-related alterations in sensorimotor integration following surgery, chemotherapy, or radiation therapy. Such changes may lead to inefficient, compensatory, and fatiguing movement strategies despite preserved task completion time, highlighting the relevance of movement quality as a distinct dimension of functional assessment in this population [7,8].

Despite its clinical relevance, movement quality remains insufficiently characterized in routine oncology rehabilitation. Existing assessment approaches often rely on subjective observational ratings or require specialized laboratory-based motion capture systems, limiting objectivity, feasibility, and scalability in clinical settings. In addition, many standard mobility assessments emphasize familiar or highly practiced tasks, which may fail to adequately challenge real-time sensorimotor control and thus underestimate qualitative movement deficits [9]. Together, these limitations underscore the need for standardized and objective methods capable of quantifying movement quality during functional task performance in cancer survivors [10].

Accordingly, the purpose of this study was to develop and validate a standardized, video-based movement quality assessment for breast cancer survivors. The assessment, termed the Rehabilitation Movement Assessment Protocol (ReMAP), was designed to evaluate postural stability, coordination, and movement efficiency using sequential, unfamiliar functional tasks that emphasize real-time sensorimotor processing. Using kinematic metrics derived from video-based pose estimation, we examined the construct validity and reliability of the assessment, with the goal of establishing a clinically feasible tool for quantifying movement quality in oncology rehabilitation.

Methods

Study Design

This study employed a cross-sectional validation design to develop and evaluate a standardized movement quality assessment for breast cancer survivors, termed the Rehabilitation Movement Assessment Protocol (ReMAP). The assessment consists of sequential, unfamiliar functional movement tasks intended to emphasize real-time sensorimotor processing rather than learned or habitual movement patterns. Analyses were conducted using baseline data from a single assessment session to establish construct validity and within-session internal reliability. Accordingly, this study focused exclusively on evaluating the measurement properties of the ReMAP Assessment, without examining intervention effects or longitudinal change.

Setting and Eligibility Criteria

This study was conducted between January 2023 and June 2024 across cancer rehabilitation centers affiliated with seven university hospitals in Korea. Recruitment and intervention were implemented at three hospital-based cancer rehabilitation centers. Eligible participants were women aged 18–65 years with a diagnosis of breast cancer who had completed curative treatment (surgery, chemotherapy, and/or radiotherapy) at least 3 months prior to enrollment and within the preceding 10 years. Potentially eligible participants were identified through clinical records and referrals for cancer rehabilitation or follow-up care, based on breast cancer diagnosis, treatment history, and current functional status. Eligibility criteria included the ability to ambulate independently without assistive devices and to follow verbal instructions required for task performance. Participants were excluded if they had acute musculoskeletal injuries, neurological disorders unrelated to cancer, or other medical conditions that could substantially interfere with safe execution of the assessment tasks.

The study sample constituted a convenience series of participants who met the eligibility criteria and consented to participate during the recruitment period. The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Boards of all participating institutions. Written informed consent was obtained from all participants.

ReMAP Movement Quality Assessment

The ReMAP Assessment was designed to evaluate qualitative aspects of movement through a series of sequential, unfamiliar functional movement tasks that emphasize real-time sensorimotor processing rather than task familiarity. The assessment consisted of three standardized paired task sequences, each comprising two task-distinct subtasks performed continuously without

pauses during evaluation sessions. Tasks were selected to challenge key components of movement quality, including forward weight shift, lateral stability, single-leg balance, trunk rotation, bilateral coordination, and multi-directional stepping. Participants performed the assessment barefoot or in standard footwear, without assistive devices, under the supervision of a trained assessor. Standardized verbal instructions were provided prior to each task, and no physical guidance or feedback was given during task execution. and all tasks were selected to be functionally relevant, low risk, and feasible for outpatient cancer survivors. Task difficulty was standardized across participants, and the assessment was terminated if participants reported pain, dizziness, or instability that compromised safety. No adverse events occurred during assessment administration. All tasks were administered in a standardized order by trained assessors according to a predefined protocol (Supplementary Methods 1). The conceptual framework of the ReMAP Assessment is illustrated in Figure 1.

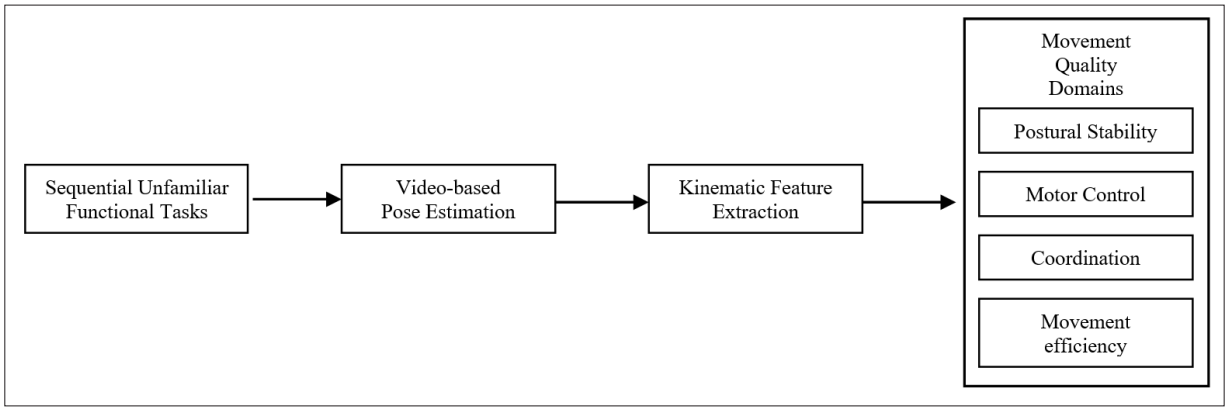

Figure 1: Conceptual Framework of the Rehabilitation Movement Assessment Protocol (ReMAP)

ReMAP is a standardized, video-based movement quality assessment consisting of sequential, unfamiliar functional tasks designed to emphasize real-time sensorimotor processing. RGB video is processed using pose estimation to derive kinematic metrics representing multiple domains of movement quality, including postural stability, coordination, movement efficiency, and motor control.

Video Recording and Pose Estimation

Movement performance during the ReMAP Assessment was recorded using standard RGB video cameras positioned to capture full-body motion in the frontal and lateral planes. Video data were processed using MediaPipe Pose (BlazePose) to extract 33 anatomical landmarks representing major joints and body segments. Landmark trajectories were visually inspected for tracking errors and subsequently filtered using a low-pass filter to reduce noise prior to kinematic analysis.

Kinematic Outcome Metrics

Kinematic metrics were derived a priori to reflect four predefined domains of movement quality: postural stability, motor control, inter-limb coordination, and movement efficiency (Supplementary Methods 2).

Postural stability was quantified as the variability of center-of-mass displacement in the mediolateral direction, operationalized as the standard deviation of center-of-mass (COM) position over time. Higher values indicated poorer postural stability. Motor control was quantified as the using trajectory variability metrics, defined as the variability of limb movement paths across repeated executions of the same task. Trajectory variability was operationalized as the standard deviation of task-specific movement trajectories, capturing the consistency and precision of motor execution under identical task demands. Higher values indicated poorer motor control and less consistent movement execution. Inter-limb coordination was quantified using coordination indices derived from correlations between bilateral limb trajectories, with analyses focused on the lateral view to capture side-to-side coordination demands. Higher values indicated better coordination. Movement efficiency was quantified using an energy ratio metric comparing observed mechanical energy expenditure during task performance with a theoretical minimum-energy trajectory. Higher values indicated lower movement efficiency. For each participant, metrics were calculated for each task and subsequently averaged across tasks to generate domain-level summary values.

Construct Validity

Construct validity was examined by evaluating associations between ReMAP-derived kinematic metrics and established clinical measures of balance and functional mobility. Clinical reference measure included the Timed Up and Go (TUG) test. Construct validity was examined using both Pearson and Spearman correlation coefficients to evaluate associations between ReMAP-derived kinematic metrics and clinical reference measures. Based on theoretical considerations, we hypothesized moderate associations between ReMAP metrics and balance-related measures and weaker associations with time-based functional performance.

Reliability

Reliability of the ReMAP Assessment was evaluated using within-session internal consistency based on intraclass correlation coefficients (ICC). ICC values were interpreted according to established guidelines, with higher values indicating greater reliability.

Statistical Analysis

Descriptive statistics were calculated for participant characteristics and all kinematic metrics. Continuous variables

are reported as mean ± standard deviation or median with interquartile range, as appropriate. Construct validity was examined using Pearson and Spearman correlation coefficients to evaluate associations between ReMAP-derived kinematic metrics and clinical reference measures. Reliability of the ReMAP Assessment was evaluated using within-session internal consistency based on intraclass correlation coefficients (ICC) with corresponding 95% confidence intervals. All statistical analyses were performed using Stata version 19 (StataCorp, College Station, TX, USA). All statistical tests were two-sided, and a p-value < 0.05 was considered statistically significant.

Results

Participant Characteristics

Baseline demographic and clinical characteristics of the participants are summarized in Table 1. The study included 70 breast cancer survivors with a mean age of 49.7 ± 6.5 years. Approximately half of the participants had completed college education or higher (51.4%), and 48.6% were employed at the time of assessment. The cohort was recruited from outpatient rehabilitation clinics and represents a clinically relevant population of cancer survivors receiving follow-up or rehabilitative care. Most participants were diagnosed with stage II (48.6%) or stage III disease (38.6%), while a smaller proportion had stage I disease (12.9%). This distribution reflects a population with moderate to advanced disease severity, consistent with referral patterns to rehabilitation services following primary cancer treatment. All participants had a confirmed diagnosis of breast cancer and therefore constituted a single target-condition cohort. The ReMAP Assessment and clinical reference measures were administered during the same baseline evaluation session, and no clinical interventions occurred between the index test and the reference standard assessments. Accordingly, the time interval between assessments was negligible, minimizing the potential for temporal or treatment-related confounding.

Table 1: Baseline Characteristics of Participants (n=70)

	N (% of sample)
Demographic	
Age (mean ± SD)	49.7 ± 6.5
Education	
High school/some college	34 (48.6)
College graduate or more	36 (51.4)
Employment	
Employed	34 (48.6)
Retired	24 (34.3)
Other not employed	12 (17.1)
Clinical	
Breast Cancer Stage at Diagnosis	
1	9 (12.9)
2	34 (48.6)
3	27 (38.6)
Primary Surgical Treatment	
Lumpectomy	37 (52.9)
Unilateral mastectomy	30 (42.9)
Bilateral mastectomy	3 (4.3)
Axillary surgery	
ALND	32 (45.7)
SLNB	38 (54.3)
Received radiation	
No	24 (34.3)
Yes	46 (65.7)
Received chemotherapy	
No	14 (20.0)
Yes	56 (80.0)
On endocrine therapy	
No	4 (5.7)
Yes	66 (94.3)

Values are presented as mean ± standard deviation or number (%). ALND, axillary lymph node dissection; SLNB, sentinel lymph node biopsy.

Descriptive Statistics of ReMAP Kinematic Metrics

Summary statistics for the ReMAP-derived kinematic metrics are presented in Table 2. Across participants, mediolateral center-of-mass sway, inter-limb coordination indices, and energy ratio values exhibited broad distributions without evidence of floor or ceiling effects. Metrics derived from different movement quality domains demonstrated distinct distributions, supporting the conceptual separation of postural stability, coordination, and movement efficiency as related but nonredundant constructs.

Measurement error indices derived from reliability estimates are presented in Table 2. Standard error of measurement (SEM) and minimal detectable change at the 95% confidence level (MDC_{95}) varied by metric, reflecting domain-specific differences in task sensitivity and measurement precision.

Table 2: Descriptive Statistics of ReMAP Movement Quality Metrics

Domain	Metric	Mean ± SD	Median [Q1, Q3]	SEM	MDC95
Postural stability	COM sway (ML)	78.38 ± 22.66	74.24 [66.42, 89.37]	20.4	56.5
Motor control	Trajectory variability	72.88 ± 38.90	84.17 [25.61, 98.28]	24.4	67.7
Coordination	Lateral correction rate	1.82 ± 2.72	0.15 [0.13, 5.40]	0.65	1.80
Efficiency	Energy ratio	61.26 ± 43.74	62.44 [20.17, 84.08]	31.8	88.0

Values are presented as mean ± SD and median [interquartile range]. Participant-level metrics were calculated by averaging task-level values across all task sequences. SEM indicates standard error of measurement. MDC_{95} represents the minimal detectable change at the 95% confidence level, calculated as $SEM \times 1.96 \times \sqrt{2}$.

Construct Validity

Construct validity analyses demonstrated generally weak associations between ReMAP-derived kinematic metrics and clinical reference measures of functional mobility and balance (Table 3). Among coordination-related metrics, lateral correction rate showed a significant monotonic association with TUG performance (Spearman $\rho = 0.295$, $p = 0.015$), whereas Pearson correlation was not significant, consistent with a non-normal distribution and a rank-based relationship. Other metrics, including postural stability (COM sway), movement efficiency (energy ratio), and motor control (trajectory variability), demonstrated weak and non-significant associations with TUG.

Overall, these findings support the construct validity of the ReMAP Assessment by demonstrating that its kinematic metrics capture qualitative dimensions of movement behavior that are not strongly reflected by commonly used performance-based mobility measures.

Table 3: Construct Validity of ReMAP Movement Quality Metrics

Metric	Reference	Pearson r (p)	Spearman ρ (p)
COM sway (mediolateral)	TUG	0.018 (0.883)	0.016 (0.898)
Trajectory variability	TUG	-0.018 (0.882)	0.010 (0.935)
Lateral correction rate	TUG	0.130 (0.293)	0.295 (0.015)
Energy ratio	TUG	-0.049 (0.691)	-0.042 (0.735)

Pearson and Spearman correlation coefficients were calculated to examine associations between ReMAP-derived kinematic metrics and established clinical reference measures. Clinical reference measure included the Timed Up and Go test (best of two trials). Participant-level ReMAP metrics were calculated by averaging task-level values across all task sequences.

Internal Reliability

Within-session internal reliability was assessed using intraclass correlation coefficients across repeated task segments (Table 4). Reliability varied across movement quality domains.

Coordination-related metrics demonstrated the highest reliability, with lateral correction rate exhibiting excellent internal reliability (ICC [3,1] = 0.94, 95% CI 0.92–0.96). Motor control, quantified by trajectory variability, showed good reliability (ICC [3,1] = 0.61, 95% CI 0.50–0.70). Movement efficiency (energy ratio) demonstrated moderate reliability (ICC [3,1] = 0.47, 95% CI 0.36–0.59). In contrast, COM sway (mediolateral) showed lower reliability (ICC [3,1] = 0.17, 95% CI 0.09–0.30).

Table 4: Internal reliability of ReMAP movement quality metrics

Metric	ICC model	ICC (95% CI)
COM sway (mediolateral)	ICC(3,1)	0.17 (0.09-0.30)
Trajectory variability	ICC(3,1)	0.61 (0.50-0.70)
Lateral correction rate	ICC(3,1)	0.94 (0.92-0.96)
Energy ratio	ICC(3,1)	0.47 (0.36-0.59)

Intraclass correlation coefficients (ICCs) were calculated to evaluate within-session internal reliability of ReMAP-derived kinematic metrics across repeated task segments. ICCs were estimated using a two-way mixed-effects model for single measures and consistency (ICC [3,1]). Participant-level metrics were derived from task-level values obtained from sequential functional task segments.

Discussion

This study developed and validated a standardized, video-based assessment for quantifying movement quality in cancer survivors. Using sequential, unfamiliar functional tasks and kinematic metrics derived from pose estimation, the ReMAP Assessment demonstrated favorable measurement properties, including construct validity and internal reliability. Importantly, the assessment captured qualitative dimensions of movement control postural stability, inter-limb coordination, and movement efficiency-that are not fully reflected by commonly used performance-based measures of functional mobility.

The present findings support movement quality as a construct that is conceptually and empirically distinct from traditional functional performance outcomes. ReMAP-derived metrics demonstrated theoretically consistent associations with balance-related clinical measures, while relationships with time- or speed-based mobility measures were comparatively weaker. This pattern aligns with the premise that movement quality reflects underlying sensorimotor control strategies governing how movements are stabilized, coordinated, and executed, rather than the speed at which tasks are completed. In cancer survivorship, where functional limitations often arise from treatment-related alterations in motor control rather than overt neurological injury or generalized deconditioning, such qualitative deficits may persist despite preserved task performance. Construct validity analyses revealed generally weak associations between ReMAP movement quality metrics and clinical reference measures such as TUG and one-leg standing time. Rather than indicating poor validity, this pattern supports the conceptual distinction between movement quality and performance-based outcomes. TUG and balance tests primarily reflect task completion time or endurance, whereas ReMAP metrics characterize how movements are executed, including control strategies, efficiency, and coordination. The significant monotonic association between lateral correction rate and TUG suggests that coordination-related correction behavior may contribute to functional mobility performance, while other qualitative aspects remain largely independent of task speed or duration.

Functional impairment in cancer survivors differs in important ways from that observed in populations with central neurological disorders or age-related decline [11]. Cancer treatments such as surgery, chemotherapy, and radiation therapy can disrupt sensorimotor integration, proprioception, and coordination, leading to inefficient and fatiguing movement strategies [5-12]. These changes may not be readily detected by conventional performance-based mobility tests but can substantially affect functional confidence and daily activity [13,14]. The ReMAP Assessment directly addresses this gap by providing a structured means of quantifying treatment-related alterations in movement

quality that are characteristic of cancer survivorship [15]. A key strength of the ReMAP Assessment is its use of sequential, unfamiliar functional tasks performed without pauses. By minimizing reliance on task familiarity, the assessment challenges real-time sensorimotor processing and increases sensitivity to qualitative movement deficits. In addition, the use of standard RGB video and pose-estimation technology enables objective, quantitative analysis of movement quality without the need for laboratory-grade motion capture systems or wearable sensors. This approach enhances feasibility, scalability, and potential clinical adoption while maintaining methodological rigor.

Prior studies in cancer survivorship have primarily relied on performance-based measures such as gait speed, balance duration, and the Timed Up and Go test to characterize functional mobility. While these measures are clinically useful, they predominantly capture task completion time or endurance and provide limited insight into how movements are executed [16,17]. Previous work has demonstrated that cancer survivors frequently exhibit balance impairments and altered movement strategies despite preserved muscle strength or aerobic capacity, suggesting a dissociation between physical capacity and movement control [18,19]. Consistent with this literature, the generally weak associations observed between ReMAP movement quality metrics and conventional clinical reference measures support the conceptual distinction between movement quality and performance-based outcomes. Rather than indicating poor validity, these findings suggest that ReMAP captures qualitative dimensions of movement behavior—such as coordination strategies, movement efficiency, and motor control that are not reflected by time-based functional tests [20]. Similar dissociations have been reported in movement science research, in which kinematic measures of variability and coordination provide complementary information beyond traditional clinical scores [21].

The domain-specific reliability patterns observed in the present study further align with prior work on motor control and movement variability. Coordination-related metrics demonstrated high reliability, consistent with evidence that inter-limb coordination and corrective motor strategies represent relatively stable individual characteristics [21,22]. In contrast, postural sway exhibited lower reliability, likely reflecting its sensitivity to task-specific balance demands rather than measurement instability. This pattern parallels findings from postural control research, where variability is understood as an adaptive response to task constraints rather than random error [15-23].

Overall, internal reliability differed across movement quality domains, ranging from low reliability for postural sway to excellent reliability for coordination-related metrics. Movement efficiency and motor control measures demonstrated moderate to good reliability, indicating domain-specific variation in measurement stability. underlying control characteristics captured by the ReMAP Assessment. Coordination-related metrics demonstrated the highest reliability, suggesting that corrective coordination strategies represent stable, trait-like features of individual movement behavior that are consistently expressed across varying task demands. Measures of movement efficiency and motor control showed moderate to good reliability, reflecting their dependence on both individual movement strategies and task-specific constraints.

In contrast, postural sway exhibited lower reliability, which likely reflects its sensitivity to immediate task demands rather than measurement instability. In the context of sequential and unfamiliar functional tasks, variability in postural sway may represent adaptive adjustments to changing balance requirements rather than random error [24]. This interpretation aligns with contemporary movement science perspectives, in which variability is understood as a functional component of motor control rather than an undesirable source of noise [15-25]. Together, these findings support the conceptual coherence of the ReMAP framework and underscore the importance of interpreting reliability within the context of domain-specific movement demands.

The availability of a standardized and objective movement quality assessment has important implications for oncology rehabilitation. Clinically, the ReMAP Assessment may assist in identifying specific qualitative movement impairments that are not apparent from conventional mobility tests, thereby informing individualized rehabilitation planning and risk stratification. From a research perspective, the assessment provides a quantitative framework for studying movement quality as a distinct outcome, facilitating mechanistic investigations and enabling comparison across studies without reliance on subjective observational ratings. By providing SEM and MDC_{95} values, this study offers practical thresholds for interpreting meaningful differences in movement quality metrics. These indices enable clinicians and researchers to distinguish true changes from measurement variability, enhancing the utility of ReMAP metrics for clinical assessment and research applications.

Limitations

Several limitations should be considered when interpreting these findings. First, reliability was assessed within a single session using repeated task segments rather than across separate testing sessions. Although this approach is appropriate for evaluating internal consistency of algorithm-derived metrics, future studies should examine test-retest reliability across days. Second, construct validity was assessed using established clinical measures of balance and functional mobility; inclusion of additional reference measures related to sensorimotor integration or fall risk may further strengthen validation. Third, the study sample consisted of cancer survivors who were able to ambulate independently, which may limit generalizability to individuals with more severe mobility impairments or advanced disease. Fourth, while video-based pose estimation offers practical advantages, tracking accuracy may be influenced by recording conditions and should be considered when implementing the assessment in different clinical environments. Finally, responsiveness and longitudinal sensitivity were not evaluated in this study, as the primary aim was to establish foundational measurement properties of the assessment.

Conclusions

The ReMAP Assessment provides a feasible, standardized, and objective approach to quantifying movement quality in cancer survivors. The assessment demonstrates acceptable construct validity and domain-specific internal reliability, supporting its

use as a complementary tool to conventional performance-based mobility tests. By capturing qualitative dimensions of movement behavior that are not reflected by time-based outcomes, ReMAP has the potential to enhance functional assessment and inform targeted rehabilitation strategies in oncology settings.

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Supplementary Table 1: ReMAP Assessment Tool

Task pair	Subtask	Designation	Movement focus	Task description
1	1A	Stretch arm on semi-forefoot step	Forward weight shift	Participants performed the assessment barefoot or in standard footwear, without assistive devices, under the supervision of a trained assessor. Standardized verbal instructions were provided prior to each task, and no physical guidance or feedback was given during task execution. Each task was performed once per assessment session, and all movements were recorded using a fixed-position RGB camera for subsequent kinematic analysis.
1	1B	Windmill guarding	Trunk rotation	From an upright stance, the participant performs alternating trunk rotations with coordinated arm movements resembling a windmill motion. This task emphasizes trunk rotation control and upper–lower body dissociation under dynamic balance demands.
2	2A	Raise arms on one-leg standing	Single-leg balance	The participant stands on one leg while raising both arms overhead in a smooth, continuous motion. This task challenges single-leg postural control, coordination, and vertical stability.
2	2B	Side guarding	Lateral stability	From a neutral stance, the participant performs lateral stepping with simultaneous arm guarding movements. This task targets mediolateral balance control and corrective coordination strategies.
3	3A	Horizontal guarding	Bilateral coordination	The participant executes bilateral arm movements in the horizontal plane while maintaining an upright stance. This task assesses bilateral coordination and inter-limb synchronization during static postural control.
3	3B	Triangle step	Multi-directional stepping	The participant performs a sequence of forward, lateral, and diagonal steps forming a triangular pattern. This task evaluates multi-directional stepping control, dynamic balance, and movement planning.

Supplementary Table 2: Definition and interpretation of ReMAP movement quality metrics used in the present study

Domain	Metric	Definition	Unit	Interpretation
Postural stability	COM sway (ML)	Standard deviation of center-of-mass displacement in the mediolateral direction during task performance	Ratio of observed mechanical energy expenditure to the theoretical minimum-energy trajectory	Lower values indicate greater postural stability
Motor control	Trajectory variability	Standard deviation of movement trajectories across repeated executions	cm (or normalized unit)	Lower values indicate more consistent and precise motor control
Coordination	Lateral correction rate	Frequency or magnitude of corrective lateral adjustments during task execution	unitless	Higher values indicate more effective coordination and corrective control

Movement efficiency	Energy ratio	Ratio of observed mechanical energy expenditure to theoretical minimum	unitless	Lower values indicate greater movement efficiency

All metrics were derived from RGB video using pose estimation and calculated at the participant level by averaging task-level values across all ReMAP task sequences.

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