TITLE: Effects of Exercise on Cancer Treatment Efficacy: A Systematic Review of Preclinical and Clinical Studies

RUNNING TITLE: Exercise and Cancer Treatment Efficacy

Lin Yang, PhD\textsuperscript{1,2}; Andria R. Morielli, PhD\textsuperscript{1}; Emily Heer, MSc\textsuperscript{1}; Amy A. Kirkham, PhD\textsuperscript{3}; Winson Y. Cheung, MD, MPH\textsuperscript{4,5}; Nawaid Usmani, MD\textsuperscript{6}; Christine M. Friedenreich, PhD\textsuperscript{1,2}; Kerry S. Courneya, PhD\textsuperscript{7}

\textsuperscript{1}Department of Cancer Epidemiology and Prevention Research, Cancer Care Alberta, Alberta Health Services, Calgary, AB, Canada
\textsuperscript{2}Departments of Oncology and Community Health Sciences, Cumming School of Medicine, University of Calgary, Calgary, AB, Canada
\textsuperscript{3}Faculty of Kinesiology & Physical Education, University of Toronto, Toronto, ON, Canada
\textsuperscript{4}Department of Medical Oncology, Tom Baker Cancer Center, Calgary, AB, Canada
\textsuperscript{5}Department of Oncology, Cumming School of Medicine, University of Calgary, Calgary, AB, Canada
\textsuperscript{6}Department of Oncology, University of Alberta and Division of Radiation Oncology, Cross Cancer Institute, Edmonton, AB, Canada
\textsuperscript{7}Faculty of Kinesiology, Sport, and Recreation, University of Alberta, Edmonton, AB, Canada
Correspondence: Dr. Lin Yang, PhD, Department of Cancer Epidemiology and Prevention Research, Cancer Care Alberta, Alberta Health Services, 5th Floor, Holy Cross Centre, Box ACB, 2210 - 2 St. SW, Calgary, AB T2S 3C3.

Email: Lin.Yang@albertahealthservices.ca; Tel: 403-698-8156

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ABSTRACT

We systematically reviewed and synthesized evidence on the impact of physical activity/exercise on cancer treatment efficacy. We included six preclinical and seven clinical studies. Exercise significantly enhanced the efficacy of chemotherapy and tamoxifen in seven of eight rodent models in either an additive, sensitizing, or synergistic manner. In clinical studies, preliminary evidence indicates that exercise during neoadjuvant, primary, and adjuvant treatment may enhance efficacy of cancer therapies; however, no clinical study was designed for this purpose. Here we discuss the biological mechanisms of exercise-associated enhancement of therapeutic efficacy and propose future research directions to definitively examine the effects of exercise on cancer treatment and patient outcomes.
INTRODUCTION

Post-diagnosis physical activity, defined as any bodily movement produced by skeletal muscles that requires energy expenditure, was associated with improved cancer-specific and overall survival in observational studies (1,2). Exercise, defined as a specific type of physical activity that is planned, structured and repeatedly done to improve or maintain physical fitness, has been proposed to improve cancer survival outcomes via three main clinical pathways: (i) direct effects on tumor growth and metastasis, (ii) improved treatment completion rates, and/or (iii) improved cancer treatment efficacy (3) (Supplementary Figure 1). In terms of direct effects, exercise has been shown to slow tumor growth and progression in preclinical studies (4,5). While the biological mechanisms underlying this relationship have not been confirmed, there is emerging evidence that exercise induces anti-neoplastic effects at both the systemic and intra-tumoral levels (5-7). In regards to improved treatment completion, clinical studies have shown that exercise improves some cancer treatment-related side effects (8) which may translate into improved cancer treatment completion rates (9).

The effects of exercise on cancer treatment efficacy, however, have received less attention. The potential interactions between exercise and cancer treatment efficacy are complex and may depend on whether or not exercise has direct effects on tumor growth and metastases (3). The systemic (e.g., improved immune and metabolic function, reduced inflammation) and local (e.g., improved tumor vascularization, blood flow, and infiltration) effects of exercise may improve the efficacy of cancer treatments (5). Theoretically, exercise may improve cancer treatment efficacy in an additive, sensitizing, or synergistic fashion (Table 1A) (3). Moreover,
these proposed effects may be impacted by the tumor site, the treatment regimen, and individual factors (3).

To our knowledge, no systematic review has synthesized and evaluated existing research on exercise and cancer treatment efficacy. The aim of this systematic review was to provide an overview of the current preclinical and clinical evidence of the impact of physical activity and exercise on cancer treatment efficacy outcomes. We also sought to highlight important knowledge gaps and provide key recommendations for future research on this critically important topic.
METHODS

This systematic review was registered with PROSPERO *a priori* (CRD42020142954) and executed using the PRISMA statement guidelines. Two reviewers (ARM and LY) independently searched three electronic databases (MEDLINE, Embase, Scopus) for preclinical and clinical studies of exercise (or physical activity) that included a treatment efficacy outcome measure and were published between December 31, 1999 and August 4, 2019. No search limits were set for study design, study population, or the language of publication. The search syntax was limited to treatment efficacy, cancer treatment, and exercise terms (*Supplementary Table 1*) combined using an “AND” term. The systematic search was updated on February 10, 2021.

*Study selection and inclusion criteria*

Two reviewers (LY and ARM) each screened half of the titles and abstracts to remove obviously irrelevant articles, with these decisions being mutually verified. The remaining abstracts were assessed for inclusion by one reviewer (LY) and exclusions were checked by the other reviewer (ARM). The full text of all remaining studies was obtained and assessed independently for final inclusion by two reviewers (LY and ARM), with any discrepancies resolved by discussion.

Observational and experimental studies of physical activity (or exercise) with at least one “non-active” comparison (or control group) reporting a measure of treatment efficacy were eligible for inclusion. Treatment efficacy endpoints were based on tumor assessment and included measures of tumor response in accordance with the RECISIT 1.1 criteria for solid tumors (10). We also included disease-free survival and overall survival as clinical endpoints,
with overall survival considered the most important measure of cancer treatment benefit in clinical trials. For ease of interpretation, treatment efficacy endpoints were grouped according to tumor response outcomes and time-to-event outcomes. Exercise intervention trials that enrolled participants both on and off cancer treatment were included if treatment efficacy outcomes were reported separately for patients on treatment. We excluded cross-sectional studies, published protocols, studies reporting treatment efficacy outcomes in relation to exercise performed after the completion of cancer treatment, and studies reporting multimodal interventions where the isolated effects of exercise could not be determined.

**Data extraction and data synthesis**

For each included study, one reviewer extracted the data (EH), a second reviewer (LY) verified the extracted data and made a summary assessment of study validity, and a third reviewer (ARM) verified the assessment of validity. Any discrepancies were resolved by discussion. Data on the following factors was extracted for each study: Endnote record number, name of the first author, year of publication, journal, country, study objective, study design, measures of exercise for observational studies, and content of the intervention for interventional studies; the procedures for defining, recruiting, and sampling from the intervention and control groups; the characteristics and sample size of the study population; the frequency and duration of follow-up; the definition and measures of treatment efficacy; results of any descriptive data and statistical tests reported; subgroup analyses, and any evidence relating to effects on other tumor-related outcomes. When studies reported results from the same experiment (11,12), the outcome data from the earlier publication (12) was not included.
**Strategy for data synthesis**

Data extracted from preclinical and clinical studies were synthesized separately. We summarized clinical studies by cancer treatment setting. Where possible, we presented the absolute and relative differences between the exposed/intervention and non-exposed/control groups in a quantitative narrative synthesis. Given the heterogeneity of the tumor sites, treatment modalities, study designs, and outcome metrics, a meta-analysis was not performed.

**Risk of bias (quality assessment)**

The methodologic quality of the included clinical studies was assessed using the Risk of Bias 2 (RoB2) assessment tool, an update to the original Cochrane risk of bias tool (13). The RoB2 evaluates the following domains in randomized controlled trials: randomization process; deviations from the intended interventions; missing outcome data; measurement of the outcome; and selection of the reported result. The RoB2 was used to assess both randomized and non-randomized controlled trials in the present review for consistent evaluation. One reviewer (LY) assessed study quality which was verified by another reviewer (ARM) and any discrepancies resolved in discussion with a third reviewer.
RESULTS

A total of 18,112 articles were retrieved from the initial search, and 162 full texts were screened. An updated search conducted on February 10, 2021 retrieved one additional study (14) and one unpublished study conducted by coauthors (15) that met the inclusion criteria. Articles screened and reasons for exclusion are illustrated in Supplementary Figure 2. Thirteen studies were included in the present review.

Six preclinical studies utilized eight rodent models including: breast (n=3), melanoma (n=2), Ewing sarcoma (n=2) and pancreatic (n=1) cancers. Seven clinical studies were identified and included cancers of the breast (n=3), colon and rectum (n=2), lymphoma (n=1), and mixed sites (n=1). We summarized the study characteristics (Supplementary Table 2) and findings in absolute and relative measures (Supplementary Tables 3 and 4) for each included study.

Rodent models

All preclinical studies were full factorial designs investigating the effect of aerobic exercise (treadmill/wheel running) and concurrent cancer treatment on treatment efficacy with four study arms: (i) control, (iii) exercise alone, (iii) cancer treatment alone, and (iv) exercise + cancer treatment (sample size in each arm ranged from 5-21). All but one of the studies (16) investigated the effect of exercise on the efficacy of a single chemotherapeutic agent in breast, melanoma, pancreatic, and Ewing sarcoma cancer models. Khori et al (16) examined the effect of exercise on tamoxifen efficacy in a breast cancer model. The effect of exercise on cancer treatment efficacy for each study is summarized in Table 1B.
In 2005, Jones et al (17) conducted the first animal model (triple negative breast cancer, MDA-MB-231 grown in nude mice) of exercise and cancer treatment efficacy. Exercise alone improved 45-day survival (16%, 95% CI: 2 to 31%) compared to control (0%). However, exercise + doxorubicin resulted in a lower 45-day survival (20%, 95% CI: 7 to 33%), compared to doxorubicin alone (35%, 95% CI: 17 to 54%), suggesting an antagonistic effect of exercise on chemotherapy efficacy. In later female breast cancer models, Betof et al (ER-, 4T1 grown in immunocompetent mice) (18) and Khori et al (ER+, MC4-L2 grown in immunocompetent mice) (16) found that exercise alone reduced tumor volume compared to control (Betof: ~600 mm$^3$ vs. ~800 mm$^3$; p<0.01; Khori: 0.37 cm$^3$ vs. 1.43 cm$^3$; p<0.05). Additionally, exercise + treatment (Betof: cyclophosphamide; Khori: tamoxifen) enhanced the effect of treatment alone on reducing tumor volume (Betof: ~500 mm$^3$ vs. ~600 mm$^3$; p<0.01; Khori: 0.25 cm$^3$ vs. ~1.0 cm$^3$; p<0.05) consistent with an additive effect.

In two melanoma models (B16F10 grown in immunocompetent mice), Sturgeon et al (19) and Schadler et al (20) found that exercise alone increased tumor volume compared to control (Sturgeon: ~625 mm$^3$ vs. ~450 mm$^3$; Schadler: 1208 mm$^3$ vs. 803 mm$^3$); moreover, exercise + doxorubicin resulted in a greater tumor volume reduction compared to doxorubicin alone (Sturgeon: ~175 mm$^3$ vs. ~350 mm$^3$; p<0.05; Schadler: 365 mm$^3$ vs. 748 mm$^3$; p<0.05) suggesting that exercise had a sensitizing effect on chemotherapy efficacy.

Schadler et al (20) also reported that in a pancreatic mouse model (PDAC-4662 grown in immunocompetent mice), there was no effect (i.e., neutral) of exercise alone on tumor volume compared to control (711 mm$^3$ vs. 848 mm$^3$). Nevertheless, exercise + gemcitabine resulted in a
greater tumor volume reduction compared to gemcitabine alone (169 mm$^3$ vs. 426 mm$^3$; p<0.05) consistent with a sensitizing effect of exercise on chemotherapy efficacy.

In two separate Ewing sarcoma tumor models (A673 and TC71 grown in nude mice), Morrell et al (21) reported that exercise alone reduced tumor volume compared to control (171 mm$^3$ vs. 962 mm$^3$ and 336 mm$^3$ vs. 1109 mm$^3$). Additionally, exercise + doxorubicin resulted in a great tumor volume reduction compared to doxorubicin alone (51 mm$^3$ vs. 771 mm$^3$; p=0.02 and 186 mm$^3$ vs. 673 mm$^3$; p<0.001) demonstrating a synergistic effect of exercise on chemotherapy efficacy.

Clinical studies

Of the seven clinical studies (11,14,15,22-25) included in this systematic review, five were two-arm randomized controlled trials (11,15,22-24), and two were pre-post single-arm studies that used non-randomized comparison groups (14,25). In all studies, treatment efficacy was a secondary or exploratory outcome and reported as objective response rate (i.e., tumor volume and pathologic response rate), disease- or progression-free survival, or overall survival (or mortality) (Table 2A). The effect of exercise on treatment efficacy is summarized in Table 2B according to cancer treatment setting, type, and efficacy endpoint. The risk of bias was rated as “low” in four studies, as “some concerns” in one study, and as “high” in two studies (Supplementary Table 5) primarily due to the non-randomized design in some of the included studies.

Neoadjuvant treatment
A small pilot randomized controlled study (n=10) (23) compared the effects of a supervised boot-camp intervention to usual care on tumor volume in women receiving neoadjuvant chemotherapy for locally advanced breast cancer. In the exercise group, tumor volume was 5.06 cm at baseline and 3.59 cm post-intervention whereas, in the control group, the initial tumor volume was 4.88 cm and 3.16 cm at follow-up, suggesting no effect of exercise (p=0.76) on chemotherapy efficacy.

One study conducted in rectal cancer patients compared a supervised high-intensity interval training program during chemoradiation followed by an unsupervised moderate-to-vigorous intensity aerobic exercise program after chemoradiation (n=18) to usual care (n=18) (15). Pathologic response was complete/near complete in 56% of participants in the exercise group compared with 18% in the usual care group (95% CI: 4% to 43%; p=0.02). After adjusting for baseline clinical disease stage, the rate of complete/near complete pathologic response remained significantly higher in the exercise group (OR, 8.1, 95% CI: 1.5 to 44; p=0.016).

**Primary treatment**

In the Healthy Exercise for Lymphoma Patients (HELP) trial, Courneya et al (22) randomized 122 lymphoma survivors (44.3% receiving chemotherapy, 55.7% no treatment) to an exercise intervention (n=60) or usual care (n=62). The exercise intervention consisted of 12 weeks of thrice-weekly supervised, progressive, moderate-intensity aerobic exercise with high-intensity interval training incorporated from week 7 onwards. Exploratory analyses found a numerically superior effect of exercise on the clinical complete response (46.4% exercise vs. 30.8% control; p=0.24) in the 54 participants that were receiving chemotherapy (22).
Adjuvant treatment

Courneya et al (24) conducted the Supervised Trial of Aerobic versus Resistance Training (START) in the adjuvant chemotherapy setting which randomized 242 stage I-III breast cancer patients starting adjuvant chemotherapy to one of three arms: thrice-weekly supervised moderate-intensity aerobic training (n=78) or resistance training (n=82), or usual care (n=82) for the duration of chemotherapy (24). In an exploratory analysis, the two exercise groups were combined and compared with the usual care group during a median follow-up of 89 months. A numerically superior risk reduction was observed in the exercise group (disease-free survival: HR=0.68, 95% CI: 0.37 to 1.24; recurrence-free interval: HR=0.58, 95% CI: 0.30 to 1.11; distant disease-free survival: HR=0.62, 95% CI: 0.32 to 1.19; overall survival: HR=0.60, 95% CI: 0.27 to 1.33) in the unadjusted model. The effect of exercise on mortality risk reduction appeared to be stronger in women with HER2-positive tumors (HR=0.21, 95% CI: 0.04 to 1.02) and those who had completed at least 85% of their planned chemotherapy (HR=0.50, 95% CI: 0.25 to 1.01) (24).

Kirkham et al (14) conducted a pre-post single-arm intervention where stage I-IIIA breast cancer patients receiving adjuvant chemotherapy treatment (n=73) receiving a supervised, progressive, combined aerobic and resistance exercise program thrice-weekly were compared to a historical control group (n=85) matched for diagnoses, treatments, age, and body mass index. After treatment completion, supervised exercise sessions reduced to twice weekly for 10 weeks followed by once weekly for an additional 10 weeks. During a median follow-up of 70 months, the rate of disease progression (n=8 [11%] exercise; n=9 [11%] in historical control, p=0.974)
and overall mortality (n=5 [7%] in exercise intervention; n=6 [7%] in historical control, p=0.78) were similar in both groups.

**Inoperable metastatic**

Rief *et al* (11) randomized 60 patients with stable spinal bone metastasis of mixed cancer diagnoses receiving radiotherapy to either a supervised resistance training intervention group (n=30) or a passive physical therapy control group (n=30) to compare bone survival (time from the first diagnosis of bone metastases to death), progression-free survival, and overall survival. The intervention consisted of isometric spinal muscle training on radiotherapy days for the duration of treatment (two weeks). The physiotherapy control group received hot towel rolls with essential oils on their thorax (11). At 24 months, bone survival was 42% in the exercise group compared to 30% in the control group. Similar findings were observed for disease-free survival (24.3 months exercise vs. 20.5 months control; p=0.295), and overall survival (80% exercise vs. 70% control at 12 months, and 63% exercise vs. 57% control at 24 months; p=0.688).

Chiarotto *et al* (25) conducted a pre-post, single-arm intervention of once-weekly combined aerobic and resistance exercise training during chemotherapy for metastatic cancers. Survival outcomes were only assessed and analyzed for colorectal cancer patients (n=9 in exercise intervention, n=10 non-randomized control) (25). At eight-year follow-up, 14 out of 19 colorectal cancer patients had died, with a median survival of 2.45 years (95% CI: 1.9 to 6.4), with no effect of the exercise program on overall survival (HR=0.98, 95% CI:0.32 to 2.97).
KEY FINDINGS

In this first systematic review of the effects of exercise on cancer treatment efficacy, six preclinical studies (eight models) and seven clinical studies were included. Single agent chemotherapy was the most common treatment modality tested among animal models, with one model examining hormone therapy. Exercise appeared to reduce the efficacy of chemotherapy (i.e., an antagonistic effect) in the first model on the topic (17), but enhanced the efficacy of cancer treatments in all subsequent preclinical studies. Exercise demonstrated a simple additive effect in two models (i.e., an enhanced treatment effect consistent with the combined positive independent effects of treatment and exercise) (16,18), a sensitizing effect in three models (i.e., an enhanced treatment effect despite neutral or negative independent effects of exercise) (19,20), and a synergistic effect in two models (i.e. an enhanced treatment effect larger than the combined positive independent effects of treatment and exercise) (21). Taken together, preclinical studies suggest that exercise may improve chemotherapy efficacy irrespective of a negative, neutral or positive direct effect of exercise on tumor growth.

In the included clinical studies, there was evidence that exercise may improve the objective response rate to neoadjuvant chemoradiation in rectal cancer patients (15) and to primary chemotherapy in lymphoma patients (26). Moreover, randomized trials of exercise during adjuvant therapy showed a numerically superior effect on both disease-free survival and overall survival in patients with early breast cancer (24) and bone metastases (11). While these clinical studies suggest that exercise may enhance the efficacy of cancer treatments, there are inherent limitations in their design that confound interpretation. In the trials reviewed here, it is not possible to distinguish additive effects of exercise from interaction effects as we do not know
the independent effects of exercise on tumor behavior in these clinical settings. Nevertheless, if exercise improves treatment outcomes, it may not matter whether the effect is additive, sensitizing, or synergistic. From this perspective, better quality studies are needed showing that adding exercise to a cancer treatment improves the treatment outcome.

**BIOLOGICAL MECHANISMS**

There are several biologically plausible mechanisms whereby exercise may enhance the efficacy of cancer treatments. For instance, exercise may enhance the efficacy of cancer treatments through favorable adaptations in tumor pathway signaling, hormones, metabolism, inflammation, and immunogenicity (6). Additionally, hypoxia is one important factor that impedes the efficacy of cancer therapies including chemotherapy, radiation therapy, and immunotherapy (27). Pre-clinical prostate cancer models have demonstrated that repeated bouts of exercise improve tumor vascularization and blood perfusion (28,29). Moreover, in two preclinical prostate cancer models (30,31), tumor blood flow increased by ~200% and subsequently reduced tumor hypoxia by ~50% during an acute bout of exercise.

Notably, the pro-angiogenic nature of exercise may, in principle, fuel tumor growth in the absence of treatment (32); however, in combination with treatment, exercise may improve the delivery of anticancer therapies to the tumor through its effects on blood flow. Nevertheless, as illustrated in Table 1B, the addition of exercise to cancer treatments may reduce treatment efficacy under some scenarios (17). Although the reduced treatment efficacy associated with exercise was not statistically significant in that study, this finding highlights the need for further preclinical studies to establish the safety of exercise (or safe timing of exercise) using direct
measures of tumor physiology (i.e., tumor blood flow, tumor hypoxia, tumor vascularization, and blood perfusion) and/or treatment efficacy.

Moreover, future preclinical studies should expand to additional cancer sites and subtypes, particularly those with suboptimal treatment efficacy due to intrinsic or extrinsic biological factors that may be influenced by exercise. Future preclinical studies should also consider treatment modalities other than chemotherapy and radiation therapy, as recent animal tumor models have suggested that exercise could lead to a favorable immune environment and thus may improve the efficacy of immunotherapy (33-35). Preclinical studies are particularly important to examine the effects of exercise on treatment efficacy by incorporating measures of the aforementioned hypothesized mechanisms. In addition to the mechanisms outlined above, exercise may influence cancer treatment efficacy through its effects on drug pharmacokinetics, which are largely unknown (36). Nevertheless, exercise has the potential to influence drug absorption, distribution, metabolism, and excretion and should be investigated in future studies.

IMPLICATIONS AND FUTURE DIRECTIONS

There are several gaps in evidence identified in this systematic review that deserve attention. First, there are very few studies on this topic in both preclinical and clinical settings. Second, few studies have been designed with the goal of improving treatment efficacy and none have been powered using cancer treatment efficacy as the primary endpoint. Therefore, assessment of cancer treatment efficacy was post-hoc and exploratory in the majority of the reviewed studies. Third, the findings of the included trials are considerably heterogeneous, with mixed cancer sites and stage, the timing of the intervention relative to treatment, and treatment
regimens. Finally, very few studies included radiotherapy, immunotherapy, or other more recently developed anti-cancer therapies, which may also interact with exercise. Despite the inherent limitations of the reviewed studies, the evidence presented here is promising. In the past four decades, over 700 exercise trials in the oncology setting have been conducted to establish evidence for safety and feasibility, and whether or not exercise can improve physical function and quality of life outcomes among cancer survivors. Clinical studies with treatment efficacy as the primary outcome have been far fewer, probably because of the necessity of larger sample sizes, longer follow-up, and limited funding opportunities. Nevertheless, treatment efficacy is the most critical issue for cancer patient, and we need to develop novel methods and funding opportunities to make these trials happen. Therefore, trials designed to test the effects of exercise on cancer treatment efficacy endpoints are warranted.

Existing and future cohort studies that collect physical activity information before or during cancer treatment should consider the feasibility of data linkage in their design to examine the associations between physical activity and cancer treatment outcomes including objective response rates and survival outcomes. These studies may also begin to examine the biological mechanisms underlying the relationship between physical activity and cancer treatment efficacy by including biological samples (i.e., markers of angiogenesis, immune function, inflammation, metabolism). Alternatively, ongoing efficacy trials of new cancer treatments may collect physical activity information to examine their influence on treatment efficacy outcomes. An important consideration in observational studies is to evaluate the specific tumor types (e.g., breast cancer hormone receptor status) that are sensitive to exercise to inform targeted interventions.
The design of intervention trials during cancer treatment will depend on cancer type, treatment type and timing, and individual factors. Specifically, in clinical settings where the goal is to shrink the tumor (e.g., neoadjuvant and metastatic settings, primary radiation for prostate cancer, primary chemotherapy for lymphoma) tumor response may be evaluated using a measure of objective response. Moreover, these trials should consider incorporating assessments of the mechanisms hypothesized to improve the effectiveness of cancer treatments. To reduce participant burden and increase recruitment, parallel trials of both human and rodent models are desired to capture treatment efficacy measures in the clinical setting and supplement biological mechanistic investigation in the preclinical setting. In clinical settings where the goal is to eradicate any residual tumor cells (i.e., adjuvant treatment), time-to-event outcomes with longer follow-up will be needed. Moreover, large sample sizes will be required to evaluate these outcomes and results may be confounded if exercise crossover is offered after treatment.

There may be clinical settings where a full factorial exercise and cancer treatment efficacy trial may be feasible. Such a setting would require a new cancer treatment being compared to a placebo (or no treatment). One example is the active surveillance setting which is growing in popularity for prostate cancer patients and being considered for other cancer patients. In this setting, new treatments are being considered, and it may be possible to randomize patients to exercise in addition to the new cancer treatment, resulting in a full factorial human trial of exercise and cancer treatment efficacy. Similarly, patients with metastatic diseases might also be candidates for a full factorial exercise and cancer treatment efficacy trial if a new treatment is being compared to a placebo. If such trials are possible, it would allow for a full test of exercise
and cancer treatment main effects and interactions, similar to the rodent studies. Such studies would provide the most definitive evidence on the complex effects of exercise on cancer treatment efficacy.

CONCLUSIONS

Altogether, the findings from the included studies suggest a potential positive effect of exercise on cancer treatment efficacy. To date, no clinical study has employed treatment efficacy as the primary endpoint or been designed to disentangle the direct effects of exercise on cancer progression from the interaction effect of exercise with cancer treatments. Several proposed biological pathways support a combined positive effect of exercise and cancer treatment. Future exercise oncology research designed to focus on treatment outcomes is needed to fully establish the safety and efficacy of exercise as a standard treatment for cancer.
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Authors’ Contributions:

Conceptualization and design: L. Yang, A.R. Morielli, K.S. Courneya;

Acquisition of data: L. Yang, A.R. Morielli, E. Heer;

Analysis of data: L. Yang, A.R. Morielli;

Interpretation of data: all authors;

Writing, review and/or revision of the manuscript: all authors;

Administrative, technical, or material support: L. Yang;

Study supervision: L. Yang, K.S. Courneya, C.M. Friedenreich;

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Role of sponsor: The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; or preparation, review, and approval of the manuscript.
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### Table 1A. Possible Effects of Exercise on Cancer Treatment Efficacy\(^a\)

<table>
<thead>
<tr>
<th>Exercise Direct Effect</th>
<th>Cancer Treatment Efficacy (ES=4)</th>
<th>Reduced (ES&lt;4)</th>
<th>Unchanged (ES=4)</th>
<th>Enhanced (ES&gt;4)</th>
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</thead>
<tbody>
<tr>
<td><strong>Negative</strong> (ES=-4)</td>
<td></td>
<td>Subtractive (ES=0-3)</td>
<td>Neutralized (ES=4)</td>
<td>Sensitizing (ES&gt;4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Antagonistic (ES&lt;0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neutral</strong> (ES=0)</td>
<td></td>
<td>Antagonistic (ES&lt;4)</td>
<td>Inert (ES=4)</td>
<td>Sensitizing (ES&gt;4)</td>
</tr>
<tr>
<td><strong>Positive</strong> (ES=4)</td>
<td></td>
<td>Antagonistic (ES&lt;4)</td>
<td>Redundant (ES=4)</td>
<td>Additive (ES=5-8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Synergistic (ES&gt;8)</td>
</tr>
</tbody>
</table>

Notes: ES= hypothetical effect size
\(^a\) Adapted with permission from Morielli AR & Courneya KS. Effects of Exercise on Cancer Treatment Completion and Efficacy In: Schmitz HK, editor. Exercise Oncology: Prescribing Physical Activity Before and After a Cancer Diagnosis 2020

### Table 1B. Summary of the Effects of Exercise on Cancer Treatment Efficacy in Rodent Models

<table>
<thead>
<tr>
<th>Exercise Direct Effect</th>
<th>Cancer Treatment Efficacy</th>
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<tr>
<td><strong>Negative</strong></td>
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<td>Subtractive</td>
<td>Reduced</td>
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<td>Antagonistic</td>
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<td>Redundant</td>
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<tr>
<td>Additive</td>
<td></td>
</tr>
</tbody>
</table>

Betof 2015 (breast)

Jones 2005 (breast)

Khori.2015 (breast)

Morrell 2019 (A673 Ewing sarcoma)

Morrell 2019 (TC71 Ewing sarcoma)

Sturgeon 2014 (melanoma)

Schadler 2016 (melanoma)

Schadler 2016 (pancreatic)
Table 2A. Exercise timing, cancer treatments, and efficacy outcomes.

<table>
<thead>
<tr>
<th>Exercise Timing</th>
<th>Cancer Treatment</th>
<th>Tumor effects</th>
<th>Time-to-event</th>
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</thead>
<tbody>
<tr>
<td>Neoadjuvant or primary</td>
<td>Chemotherapy</td>
<td>Objective response rate</td>
<td>Disease-free survival</td>
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<tr>
<td></td>
<td>Radiation therapy</td>
<td>Tumor size</td>
<td>Event-free survival</td>
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<tr>
<td></td>
<td>Immunotherapy</td>
<td></td>
<td>Overall survival</td>
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<td>Adjuvant</td>
<td>Chemotherapy</td>
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<td>Immunotherapy</td>
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<td>Inoperable metastatic</td>
<td>Chemotherapy</td>
<td>Objective response rate</td>
<td>Progression-free survival</td>
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<td>Radiation therapy</td>
<td>Tumor size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Immunotherapy</td>
<td>Number of tumors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hormone therapy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2B. Summary of the Effects of Exercise on Cancer Treatment Efficacy in Clinical Studies

<table>
<thead>
<tr>
<th>Exercise Timing</th>
<th>Cancer Treatment</th>
<th>Tumor effects</th>
<th>Time-to-event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoadjuvant</td>
<td>Chemotherapy</td>
<td>↑ Rao 2012 (breast)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemoradiation</td>
<td>↑ Morielli 2021 (rectal)</td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td>Chemotherapy</td>
<td>↑ Courneya 2009 (lymphoma)</td>
<td></td>
</tr>
<tr>
<td>Adjuvant</td>
<td>Chemotherapy</td>
<td>↑</td>
<td>Courneya 2014 (breast)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>↔</td>
<td>Kirkham 2020 (breast)</td>
</tr>
<tr>
<td>Inoperable metastatic</td>
<td>Chemotherapy</td>
<td>↔ Chiarotto 2017 (colorectal)</td>
<td>↑ Rief 2016 (mixed)</td>
</tr>
</tbody>
</table>
Effects of Exercise on Cancer Treatment Efficacy: A Systematic Review of Preclinical and Clinical Studies

Lin Yang, Andria R. Morielli, Emily Heer, et al.

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