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Original research

Rehabilitation volume, psychological readiness, and motor function are important factors for a successful return to sport after anterior cruciate ligament reconstruction: A 2-year follow-up cohort study

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ABSTRACT

Objectives: To find contributors to return to sport success or time until return to sport in individuals after an anterior cruciate ligament reconstruction.
Design: Cohort study.
Methods: Secondary analysis of the data of two intervention studies.
Participants: We included adults < 36 years of age with a tendon autograft anterior cruciate ligament reconstruction who were active in any type of sport prior to the injury and aiming to return to sport. All participants were prospectively monitored for 24 months.
Interventions: At the end of the individual post-surgery rehabilitation and re-injury prevention programmes, self-report- and objective functional outcomes were quantified.
Main outcome measures: The potential return to sport success (return to the same type of sports, frequency, intensity, and quality of performance as pre-injury), secondary injuries, and all rehabilitation and training measures were prospectively monitored. To determine the contributing factors, Cox regressions for traits and baseline factors and a logistic mixed model, which also included prospective time-dependent factors, were calculated.
Results: 203 participants were included; 104 (51 % of the total sample and 68 % of the full cases) successfully returned to their sporting activity. The median duration until return to sport was 302 days (interquartile range was 114 days). Contributing factors were the type of working (blue- vs. white collar: odds ratio for return to sport = 0.51 [95 % confidence interval = 0.29 to 0.90]) and the athletic status (elite vs. non-elite: odds ratio = 2.28 [1.03 to 5.03]). Prospectively, higher rehabilitation volumes until the end of the rehabilitation were predictive for return to sport success: the odds ratio per additional hour of rehabilitation was 1.004 [1.001 to 1.006]. Functional abilities such as the normalised knee separation distance during drop jump landing (odds ratio = 0.961 [0.924 to

Abbreviations: RTS, return to sport; ACL, anterior cruciate ligament; OR, odds ratio; DRKS, German Clinical Trials Register; KOOS, Knee injury and Osteoarthritis Outcome Score; TSK, Tampa Scale of Kinesiophobia.

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0.999]) were predictive at a later stage, at the end of the re-injury prevention. Psychological readiness for return to sport was predictive at most of the timepoints: those who were confident to return to sport were more successful to return to sport at the end of the rehabilitation (odds ratio = 1.029 [1.004 to 1.056]) and at the end of the re-injury prevention (odds ratio = 1.038 [1.004 to 1.073]).

Conclusions: The most important factors for a successful pre-injury-level return to sport after anterior cruciate ligament reconstruction were the exercise volume, psychological readiness and functional hop/jump abilities. Whilst the impact of these modifiable factors was robust against multilevel modelling, the impact of athletic and working status vanishes when the prospective factors are included.

Practical implications

- Amongst the variables assessed, exercise volume, psychological readiness, and functional hop/jump abilities are the most important factors for a successful return to sport/pre-injury-level after anterior cruciate ligament reconstruction.
- Two-thirds of the athletes returned to their previous type and level of sport in the two years after an anterior cruciate ligament reconstruction.
- Relevant baseline factors for a higher probability of RTS and of a faster process were the type of worker and their athletic status: white-collar workers and elite athletes showed higher RTS rates and faster processes than blue-collar workers and non-elite athletes.
- Prospectively and statistically more important, the higher volumes of exercise and rehabilitation measures were, in particular, predictive for RTS success until the end of the rehabilitation.
- After the end of the rehabilitation, and until the end of the re-injury prevention, functional abilities such as the normalised knee separation distance and balance side hop abilities were predictive for a successful RTS.
- The only thoroughly important factor during the whole process was psychological readiness: those who were confident to RTS were prospectively more successful both at the end of the rehabilitation and at the end of the re-injury prevention.

1. Introduction

Return to sport (RTS) after an anterior cruciate ligament (ACL) rupture and reconstruction is successfully reached when one returns to the pre-injury level of sports participation. This same level is defined as returning to the same type, frequency, intensity, and quality of performance as before the injury.[1] The main purpose of the RTS process after ACL reconstruction is to guide an athlete not only back to full training, sports practice, competition and performance, but to reach these goals with a low re-injury risk.[2] Athletes, but also caregivers and other stakeholders often desire to shorten the RTP process. The aims of an early but low-risk RTS must often be weighed against each other when an athlete is guided through his/her individual RTS and released for sport.

In professional cutting and pivoting contact sports, a major share of athletes successfully return to the pre-injury type and level of their sport.[3,4] The RTS rate is lower in non-elite and recreational athletes: only 50 % to 70 % of non-elite athletes return to their pre-injury type and level of sport.[5] These lower rates call for a particular focus on finding factors of a successful versus non-RTS in elite- and non-elite athletes. In those who successfully RTS, the time until a successful pre-injury type and level RTS is highly variable.[6] Goals for RTS should thus not be based on time-based criteria.[6] In accordance with the paradigm shift away from a time- to function-based selection of the type, intensity, and progression of rehabilitation components, athletes should prospectively be monitored to determine their individual RTS clearance date. Although it may not be adequate to define a fixed time point at which RTS should be reached, the time until RTS is, nevertheless, an important factor to consider.[1] This is applicable to both elite (who are, usually, somewhat faster) and non-elite athletes.[7–9]

Due to this heterogeneity in time until RTS and the variable RTS success rates, the individual factors of a successful RTS must be known. Amongst these factors, neuromuscular functional ability,[10,11] adequate rehabilitation actions and progression (both as early and late-stage rehabilitation),[6,12,13] and psychological readiness[10,14] are known. Fear of re-injury[15] and other psychological factors, including the lack of confidence in the treated knee[15] are further named as factors of a successful RTS. Last, a lack of persisting knee symptoms/problems,[11] the Tegner activity scale,[11] calendar, biological, and career age,[16] sex/gender, interval between injury and surgery,[14] a higher frequency of pre-injury sport participation and elite versus non-elite status[14] are further important factors for a successful RTS. Consequently, a multitude of individual and spatiotemporal factors interact during the rehabilitation and RTS process. Only if the isolated and interactive contributions of these potential factors for RTS success and/or the time until RTS are known, can they be considered and, where possible, modified to improve the RTS process.

The aim of our prospective 2-year follow-up cohort study was to determine the contributions of these potential factors for RTS success and/or the time until RTS. We hypothesised that (1) exercise and rehabilitation volume, psychological readiness, and functional outcomes as well as (2) traits and baseline factors such as the type of one's work and the athletic status impact on RTS rates and the time until RTS.

2. Methods

2.1. Design and ethical aspects

This cohort study is a planned secondary analysis within the PReP Project.[17] The data included in this analysis was originally collected in an RCT and on an interventional matching cohort.

Independent institutional review board ethical approval was provided by the Ethics Committee of the Hessen Regional Medical Council (reference approval no. FF 104/2017). The date of the final approval of the study protocol was June 27, 2018. The study was planned and performed in agreement with the Declaration of Helsinki (Version Fortaleza 2013) and registered in the German Clinical Trials Register (DRKS): registration number DRKS00015313 (DRKS, drks.de; 01. October 2018).

2.2. Participants

Persons with an ACL rupture who had an appointment in one of the ten (10) study centres were informed about the possibility to be included into the study. Interested persons were afterwards screened for inclusion and recruited by means of a structured informed consent schedule. Each participant signed informed consent prior to enrolment. Inclusion criteria comprised being aged between 18 and 36 years, having an acute unilateral ACL rupture and passed (or being scheduled to) an arthroscopically assisted, anatomic ipsilateral semitendinosus tendon or semitendinosus–gracilis tendon graft ACL reconstruction.

Participants were only included if they reported to be an active athlete or sportsperson, of any type of sport, prior to the injury and aimed to return to their previous sporting activity.

Exclusion criteria comprised a meniscus lesion of larger than 2 cm, a cartilage lesion categorised as higher than ICRS II°, any previous surgery on the contralateral leg, a leg malalignment (varus or valgus) greater than 5°, multi-ligament injury patterns, post-operative complications or re-injury and/or pregnancy.

2.3. Study flow

Starting from inclusion, all participants were prospectively monitored until their individual 24-month post-reconstruction follow-up. The detailed study flow is displayed in Fig. 1. Where applicable, pre-operative rehabilitation was followed by surgery, which was followed by the post-surgery rehabilitation and re-injury prevention programme. The corresponding points in time were individually set and accompanied by process- and status-dependent measurements consisting of the self-report and functional outcomes. Other relevant aspects, such as potential RTS success, re- or secondary injuries, and all rehabilitation and training measures, were prospectively monitored throughout the total study duration by means of structured repetitive telephone interviews and, where applicable, by detailed exercise logs.

2.4. Prospectively monitored outcomes

Starting from inclusion, the participants were prospectively monitored by (repetitive) phone calls once a month until completion of the 24-month follow-up. The RTS success was given when a participant achieved his/her pre-injury level of sports participation as defined by the same type, frequency, intensity, and quality of performance as before the injury.[1] All aspects had to be reached to be rated as "successfully RTS". The success was dichotomised into no/yes based on a comparison of the current to the pre-injury type and level of sporting activity. The self-reported success of the underlying variable type, frequency, intensity, and quality was cross-validated by a pre- to current Tegner activity level comparison. Both self-reported and Tegner (only sports) activity scale-based comparisons had to be fulfilled to be rated as "RTS success". Individuals who had successfully RTS were no longer part of the later follow-up assessments (as they had already successfully RTS). The process to determine a successful RTS was made based on a graduated, functional criterion-based, and shared decision. The shared decision-making included the treating orthopaedic specialist, the physiotherapist, and the patient. The same shared approach was adopted to determine the onset and end of the respective status in the rehabilitation process.[18]

All rehabilitation measures (type, duration, intensity, frequency) between injury and reconstruction, between reconstruction and the end of the formal rehabilitation, and following the end of the formal rehabilitation were monitored. To reach that, all participants completed detailed exercise logs. The type [rehabilitation, sport type, exercise], frequency [times per week], dose [minutes per week] and mean perceived exhaustion (Borg scale ratings) [points] during each session were reported.[19] The initial phase of the rehabilitation was the medically prescribed formal rehabilitation with a graduated transition to re-injury preventive trainings. The initiation of the latter was aimed to commence at 9 to 12 months post-reconstruction. To simplify the analyses, the total rehabilitation volume in minutes was calculated.

During the repetitive phone calls, participants reported all adverse events. Particular focus was on secondary ACL injuries (ipsilateral and contralateral ACL tears). Nonetheless, all musculoskeletal conditions were monitored, irrespective of the localisation, if they lead to a time loss in any performance or not, or the severity.

It is important to note that the re-injury preventive trainings were not only individually performed but some of the participants also exercised as a part of the RCT within the PReP-project: half of the hamstring-graft participants were randomised and all quadriceps graft participants were allocated to a home-based re-injury prevention programme (Stop-X).[17] The comparator arm was usual care follow-up treatment plus guideline recurrence prevention.[17] The training frequency for both arms was three times per week, and a duration of 30 min was aimed for each session. The usual care intervention consisted of non-supervised impact exercises, dynamic exercises in the frontal plane, followed by side-cutting manoeuvres and concluded by dynamic multi-directional stabilisation exercises. The Stop-X intervention was partially supervised and completely step-wise graduated based on wound-healing and, in particular, functional progression criteria. Basic (secondary) preventive strategies, running exercises/agility exercises, self-perturbed postural control exercises, jumping exercises, plyometric and strengthening exercises were the main parts of the Stop-X-programme. Please refer to the study protocol[17] and Supplemental Table 1 for more details on this intervention. All rehabilitation measures were also categorised as have been performed during or not during pandemic-associated lockdowns.

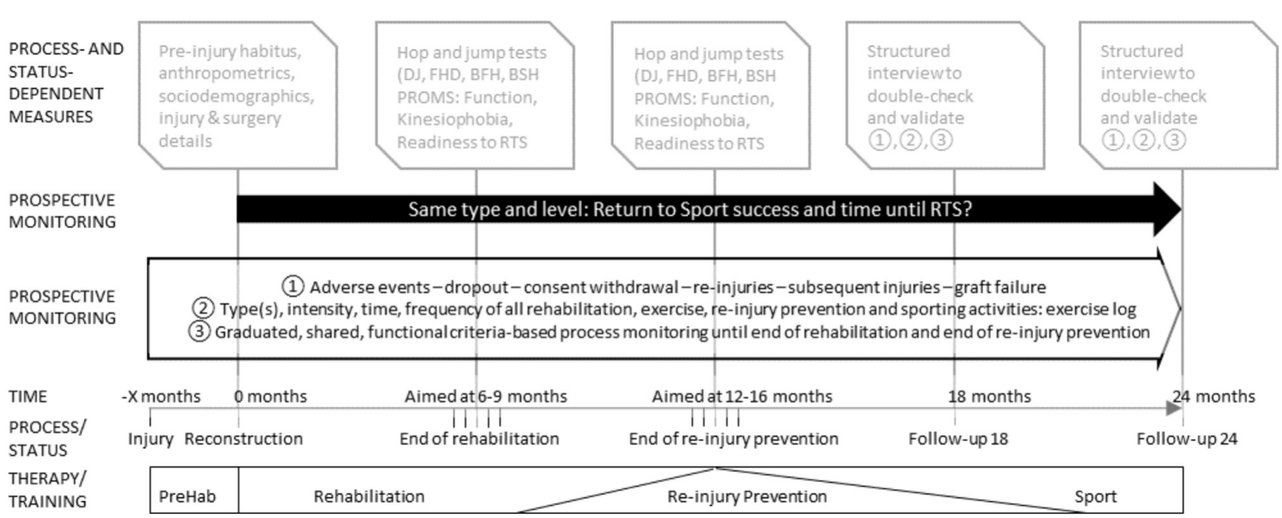

Fig. 1. Study flow. All training and rehabilitation measures (bottom) were process- and status-dependent, accompanied by measurements consisting of all self-report and functional outcomes (top). All other relevant aspects, such as potential RTS success, re- or secondary injuries, and all rehabilitation and training measures, were prospectively monitored (mid part of the figure). RTS, return to sport; DJ, drop jump; FHD, front hop for distance; BFH, balance front hop; BSH, balance side hop; PROMS, self-reported outcomes.

2.5. Outcomes assessed at the determined end points

Within the first 3 weeks after the reconstruction (telephone interview), at the end of the medically prescribed individual formal rehabilitation (self-reported and objective functional outcomes), at the end of the individual re-injury-preventive training (self-reported and objective functional outcomes), and at 18- and 24-months post-reconstruction (both by telephone interview), potential factors of the RTS process and/or time were assessed (Fig. 1).

Within the first 3 weeks after surgery, the type of work (white-collar or blue-collar worker), sociodemographic/anthropometric values, injury mechanisms (contact free, indirect contact, contact), pre-injury type(s) and level of sport and training volumes were asked. The latter were used to classify the athletic status as elite- or non-elite athletes. Elite status was defined as receiving assurance-relevant payment for the sports performance. Further surgery-specific outcomes such as the graft type were retrieved from the pseudonymised surgery reports.

The measurements at the end of the rehabilitation and at the end of the re-injury prevention follow-up consisted of batteries of hop and jump tests and questionnaires. The drop jump screening test was followed by balance front and side hops, as well as quantitative [cm] assessments of the front hop for distance performance. For the drop jump-rating,[20–22] the knee joint separation distance was rated at pre-defined points during this drop jump cycle: at the initial ground contact at the end of the drop from the box, and at the lowest point of the body's centre of gravity at the jump's reversal point. At each of these points, the distances between (1) the hip joints and (2) the middle of the two knees were measured and a percentage of the knee distance in comparison to the hip distance was calculated using the video analysis software Kinovea (France) to build the normalised knee separation distance (which yielded the outcome). The transition (difference between the normalised knee separation distance at the initial ground contact at the end of the drop from the box, and at the lowest point of the body's centre of gravity at the jump's reversal point) was selected to be included into the analyses.

For the landing quality rating, the balance front hop and the balance side hop test[23] were chosen. The quality rating criteria after landing were (1) adequate foot placement, whole sole supported, foot remained stable on the ground after landing (1 point), (2a) appropriate medial/lateral position control, knees remained in the sagittal plane, (2b) adequate knee/hip flexion, a sufficient knee flexion was performed, (3a) no lateral trunk motion, and (3b) aligned parallel to the lower leg, no excessive trunk flexion and the trunk remained in the sagittal and transversal planes.[23] Each time, the performance on the ACL reconstructed side was selected for further analysis.

For the front hop for distance (formally known as the single leg hop for distance),[10,24,25] the participant hopped as far as possible and has to land in a controlled manner. Three successful hops per leg (randomised order) were performed, with each leg's best trials [cm] being selected for further analysis. We included the limb symmetry index (percentage difference between the legs) as the outcome to be included into the models.

All hop/jump tests were performed self-administered and filmed from a frontal position (3 m distance) using the participant's own smartphone cameras. The videos were safely transferred using a safe form of big content transfer (PowerFolder Enterprise File Sync and Share; Germany) and expert-rated using the investigator-blinded videos. The participants were thoroughly educated on how to perform the jumps and hops. In cases of incorrect execution, the tests were repeated. This thorough smartphone camera-based approach is valid when compared to 3D motion-capture systems for the analyses of sagittal plane knee angles.[26] Further details on the originally sourced assessment procedure and the measurement properties of the functional outcomes are displayed in Supplemental file 1.

To assess the psychological readiness to RTS, the participants completed the questionnaire “RTS after ACL injury” (ACL-RSI).[27] The Knee injury and Osteoarthritis Outcome Score (KOOS) subscales sport (SPORT), pain (PAIN), symptoms (SYMPTOMS) and activities of all daily living (ADL) subsequently assessed the self-report knee function and symptoms.[27] Further self-reported outcomes were the Tegner activity scale (sporting activity level) and fear of movement (Tampa Scale of Kinesiophobia (TSK)).[27] All self-reported outcomes were completed online at www.soscisurvey.de. Further details on the originally sourced assessment procedure and the measurement properties of the self-report outcomes are displayed in Supplemental file 2.

2.6. Statistical analysis

First, the sample and baseline values of the anthropometric, injury-, sport-, and reconstruction-related data were described as means and standard deviations. These data were separated for those who successfully RTS within the observation period, for those who did not, and for the dropout (= censored) participants.

Subsequently, we calculated survival analyses by means of Kaplan–Meier estimators using the time until RTS success as the dependent variable. Here, the participants who dropped out, who withdrew consent, or who experienced a second injury were treated as “censored” (and not as “non-successfully RTS”). The Kaplan–Meier curves were displayed for the whole sample and separated by all available potentially relevant (real, not artificially) categorical variables. Potential determinates for RTS were elite versus non-elite athletes and white- versus blue-collar workers, and separated by pre-injury Tegner levels, sex, the type of re-injury prevention (intervention versus comparator groups), or the graft type.

These potential factors (i.e., all baseline values and traits) were then cumulatively treated as independent variables in the subsequently performed multivariate Cox regressions. The odds ratios for an RTS success with the corresponding 95 % confidence intervals were calculated for the relevant factors within a single Cox regression model.

The finally calculated logistic mixed models also included all these independent variables and the dichotomised RTS success as the dependent variable. Newly incorporated into the model were all the process and status outcomes as well as the prospectively monitored training volumes. Time since surgery was modelled as an interval scaled variable. To include the time to function paradigm shift, the individually determined assessments at the end of the rehabilitation, at the end of the re-injury prevention, at follow-up at 18 months and at 24 months post-surgery were included as the categorical variable (1 to 4). The different time [days since surgery] and assessment points as well as the individual participants were modelled as random effects, whilst all other independent variables were modelled as fixed effects. In these analyses, all participants and time points available were included, and the dropout participants were included until their dropout.

A 5 % alpha error probability was tolerated and all analyses were performed with SPSS version 28 (IBM, USA). All analyses were performed after checking the data for the needed underlying assumptions for the respective statistical test.

3. Results

3.1. Sample and baseline values

In total, 259 potentially eligible persons were screened; of these, 203 could be recruited and included into the study. From those included, 46 dropped out due to consent withdrawal during the study conduction, and 19 suffered from a subsequent injury (6 graft failure, 11 other knee injuries or subsequent issues such as arthrofibrosis, cyclops resection, arthrolysis and ankle distortion). The anthropometric, injury-, sport- and reconstruction-related data to describe the total sample is displayed in Table 1. The data is separated for those who successfully RTS within the observation period, those who did not, and the censored (dropout) participants.

Table 1
Numeric and percentage distributions of all baselines and traits. The sociodemographic, sport-, injury- and surgery-specific characteristics of the study sample are shown for the total sample and, subsequently separated into those who successfully returned to their previous sport, those who did not, and the censored ones (dropout, subsequent injuries).

Domain	Outcome	Value/unit	Total sample		RTS success (n = 104)		No RTS success (n = 34)		Censored (n = 65)	
			Number	%	Number	%	Number	%	Number	%
Socio-demographic	Sex/gender	Female	85	42	46	44.2	11	32.4	28	43.1
		Male	118	58	58	55.8	23	67.7	37	56.9
		Diverse or non-binary	0	0	0	0	0	0	0	0
Work	Type of work	White collar	154	76	82	79	20	59	52	79
		Blue-collar	49	24	22	22	14	41	13	21
Sport	Athletic status	Non-elite	187	92	95	91.3	33	97.1	59	90.8
		Elite	16	8	9	8.7	1	2.9	6	9.2
	Tegner activity level pre-injury	3	18	8.9	4	3.8	8	23.5	6	9.2
		4	44	21.7	27	26	5	14.7	12	18.5
		5	11	5.4	7	6.7	0	0	4	6.2
		6	43	21.2	19	18.3	9	26.5	15	23.1
		7	66	32.5	38	36.5	12	35.3	16	24.6
		8	5	2.5	2	1.9	0	3	3	4.6
		9	13	6.4	5	4.8	0	0	8	12.3
		10	3	1.5	2	1.9	0	0	1	1.5
Injury	Injury mechanism	Contact free	131	64.5	72	69.2	25	80.6	34	70.8
		Indirect contact	25	12.3	13	12.5	3	9.7	9	18.8
		Direct contact	18	8.9	10	9.6	3	9.7	5	10.4
Surgery	Graft type (tendon)	Semitendinosus (+gracilis)	170	83.7	92	88.5	32	94.1	46	70.8
		Quadriceps femoris	33	16.3	12	11.5	2	5.9	19	29.2

Domain	Outcome	Unit	Total sample		RTS success (n = 104)		No RTS success (n = 34)		Censored (n = 65)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Socio-demographic	Body mass index	kg/m^2	24.1	4	23.9	4.3	24.1	3.1	24.4	3.9
	Age	years	25.6	5.1	24.7	5	27.2	4.8	26.2	5.2
Sport	Training volume pre-injury	trainings/week	3.3	1.7	3.3	1.9	2.9	1.6	3.4	1.5
		min/training	95	36	97	23	88	31	95	51

SD, standard deviation.

3.2. Time to return to sport success

Overall, 104 (51 %) returned to the previous type and level of sport, and 99 did not (49 %). Amongst the latter, 34 were not successful in returning to their sports up to the end of the observation period (without being a dropout or without suffering from a subsequent issue), whilst the others either dropped out or suffered from a subsequent injury (censored data, displayed as vertical bars in Fig. 2). Thus, from the non-censored (non-dropout) patients, 24 % were not successful and 76 % were successful in their efforts to RTS. From all the participants with full datasets until the end of the observation period, 68 % successfully RTS whilst 32 % did not. The total sample RTS rates and times until RTS success are displayed in Fig. 2. The total rehabilitation process (starting from surgery (in grey), the re-injury prevention process and the follow-up measurements until 2 years post-reconstruction) is displayed. For those who successfully returned, the process, on average, lasted 313 days (median = 302 days, range from 90 to 720 days, interquartile range was 114 days).

Separated into potential factors, we found a difference in the survival curves for the RTS rates between the elite and non-elite athletes (higher RTS rates were observed in elite athletes), between the white- and blue-collar workers (the white-collars had higher success rates), and between the pre-injury Tegner levels, but not between the curves for sex, the type of re-injury prevention or the graft type (Fig. 3).

3.3. Determinants of a successful RTS — baseline values and traits

Cumulated in the multivariate Cox regression, eight variables were modelled; thereof four were excluded (pandemic-associated lockdown, sex, Tegner activity scale, re-injury prevention type) and four were included (type of worker: Blue- vs. white-collar, elite vs. non-elite athlete, time between injury and reconstruction, and graft type: hamstring vs. quadriceps tendon) in the final model (Table 2). The odds ratios for an RTS success were significant in the omnibus model for the white- versus the blue-collar workers and the elite status comparison.

3.4. Determinates of a successful RTS — prospective variables and functional outcomes

All participants were included in the following mixed models, and we only excluded certain measurements: After the exclusion of censored measurements (measurements were a dropout or a subsequent injury occurred) and the inclusion of all assessments until an individual RTS or until the end of the 24-month follow-up, a total of 308 persons ∗ measurements (data taken from 121 participants at the end of the rehabilitation, from 90 at the end of the re-injury prevention, from 61 at the 18-month follow-up and from 36 at the 24-month follow-up) could be modelled.

The final model of the prospective multilevel determinant analysis of a successful RTS led to the following main and interaction effects: time since reconstruction: $F = 0$, $p = 1$; (from now onwards interaction with the assessment numbers 1–4) exercise and rehabilitation volume since last measurement: $F = 3.8$, $p = 0.01$; confidence in knee function — sport: $F = 0.5$, $p = 0.8$; confidence to return to sport: $F = 2.8$, $p = 0.03$; kinesiophobia: $F = 0.7$, $p = 0.6$; normalised knee separation distance — transition: $F = 1.3$, $p = 0.3$; and balance side hop — ACL side: $F = 1.2$, $p = 0.3$. The detailed estimates of the overall model output are displayed in Table 3 (the variables which were excluded during modelling are displayed in the Supplemental Table 2). The underlying descriptive data of the variables included in the final mixed model are displayed in Supplemental Figs. 1 and 2.

A relevant factor for a successful return to sport was the total exercise and rehabilitation volume since the last measurement, in particular during the rehabilitation and, to a minor share, during the re-injury preventive training. Higher exercise volumes were associated with higher odds for a successful RTS. The same was found for the confidence to

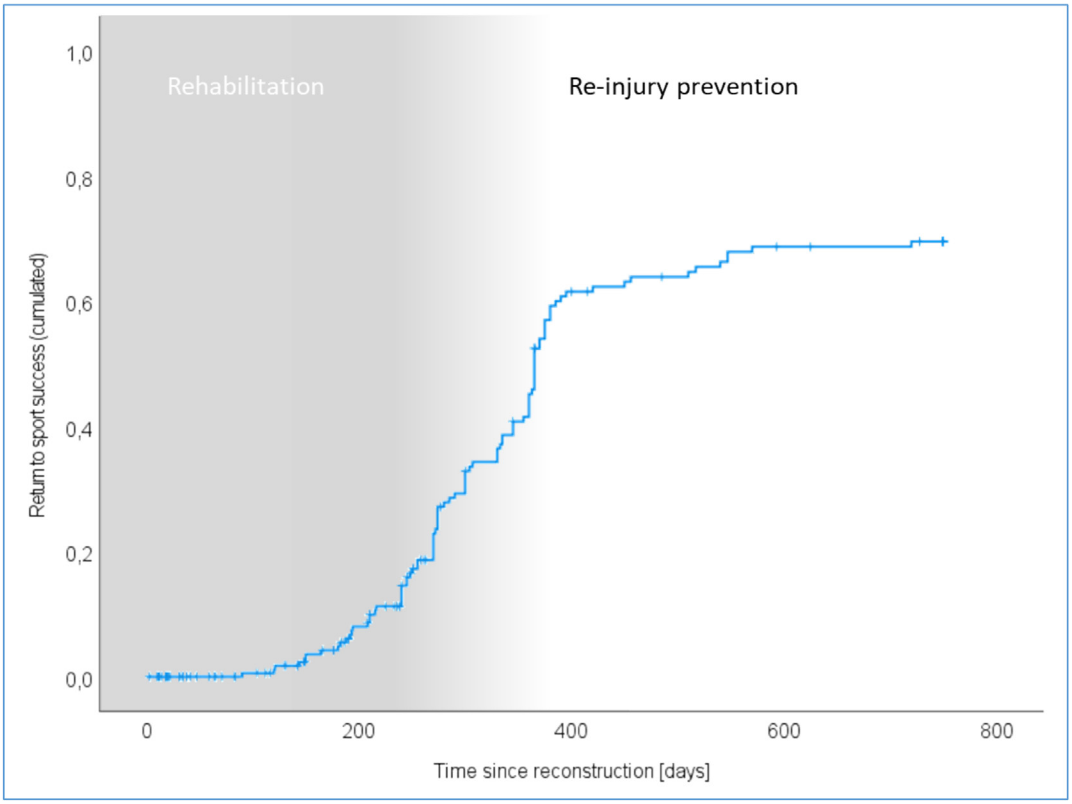

Fig. 2. Cumulative return to sport (RTS) success of the total sample, displayed in dependence of the time since reconstruction.

RTS: higher ACL-RSI values during rehabilitation and re-injury prevention led to higher odds for a successful RTS during these phases. At the end of the re-injury prevention, lower dynamic valgus values during landings after a drop jump were also associated with higher RTS-odds.

4. Discussion

4.1. Statement of principal findings and hypothesis verification

Exercise and rehabilitation volume, psychological readiness, and the knee separation distance during a drop jump are the most important key factors for a successful personalised return to sport/pre-injury-level after anterior cruciate ligament reconstruction. In our sample of mostly non-elite athletes, a major share returned to their previous type and level of sport within two years after an anterior cruciate ligament reconstruction. Important traits and baseline factors for a higher probability of a successful RTS and/or of a faster process were the type of work and the athletic status of the participants. White-collar workers and elite athletes showed faster RTS processes than blue-collar workers and non-elite athletes. Prospectively assessed, higher volumes of exercise and rehabilitation measures were particularly predictive for the RTS success up to the end of the individual rehabilitation. Afterwards, and up to the end of the re-injury prevention, the functional ability normalised knee separation distance was predictive for a successful RTS. More detailed, a lower dynamic valgus during landing led to a higher odd to earlier RTS.

The only factor which was important during both major rehabilitation phases was psychological readiness; those who reported to be psychologically more ready to RTS were more successful in RTS. The impact of exercise volume, function and psychological readiness was robust against multilevel modelling. Our hypothesis 1 is, thus, verified. In contrast, the impact of athletic and working status vanishes when the prospective factors are included. Hypotheses 2 can consequently be rejected.

4.2. Comparison with the available evidence

Many of the factors we found are already described in the literature, although mostly only described as single actors. The impact of neuromuscular functional ability,[10,11] psychological (and social) readiness to RTS,[10,14] fear of re-injury[15] and other psychological factors including the lack of confidence in the treated knee[15] on the probability to RTS remains, also when temporal structures and potential interactions are considered. The same was found for rehabilitation amounts: the impact of, in a certain way, adequate (colloquially, the more the better) rehabilitation measures and progression, both as early- and late-stage rehabilitations,[12,13,28] was important for an RTS success. Other potential contributors such as the Tegner activity scale[11] and the elite versus non-elite status[14] are only isolated predictors and, thus, may be the surrogates of other abovementioned important factors. This is, in particular, interesting for the Tegner activity scale. Different Tegner activity levels are associated with different sport- and level-specific loads and likely to be associated with considerable differences in the time until RTS. This was also found in our athletes, but only when the TAS was considered in isolation. On the other hand, we could not confirm some of the factors identified in other research, irrespective of modelling them in isolation or in our multilevel approach. Such factors were persisting knee symptoms/problems,[11] calendar, biological, and the time since having started to perform a specific type of sport,[16] sex/gender, interval between injury and surgery,[14,29] a higher frequency of pre-injury sport participation, or including concomitant knee procedures, graft type and graft fixation.[16]

4.3. Time-dependent aspects

The contributions of the athletic status and the exercise volumes on RTS were only given when these two factors were calculated separately. The higher RTS rates in the elite compared to the non-elite athletes are consistent with the literature.[3,9,29] In our sample, the elite athletes

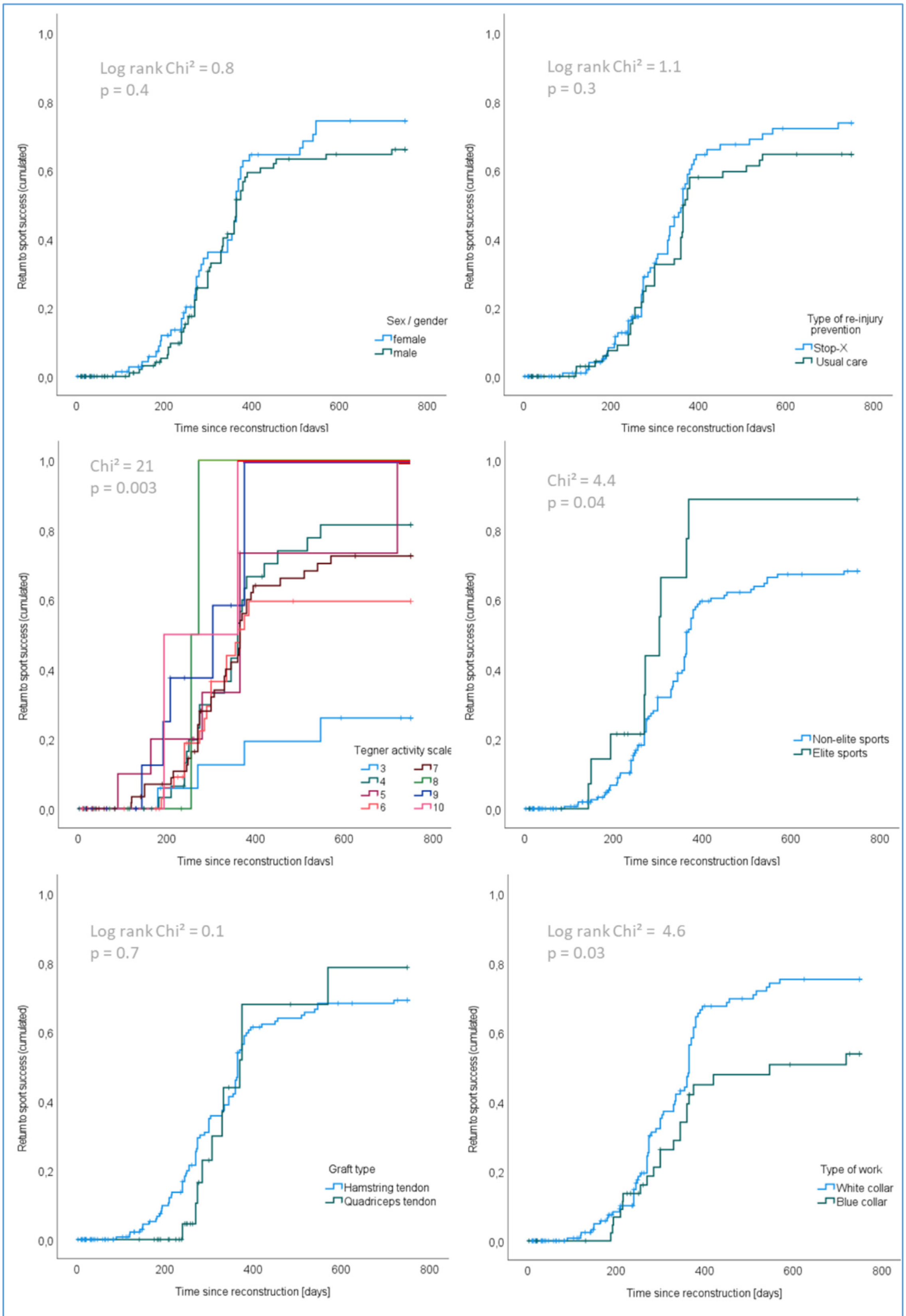

Fig. 3. Cumulative return to sport (RTS) success, grouped by the potential factors sex, the type of re-injury prevention, pre-injury Tegner levels, elite versus non-elite athletes, graft type, and between white- and blue-collar workers.

Table 2
Cox regression output. Coefficients, significances and odds ratios for RTS success are displayed for the variables included in the final model.

Included variables	B	Standard error	Wald	p-value	Odds ratio	Odds ratio: 95 % confidence interval	
						Lower level	Upper level
Type of worker: Blue- vs. white-collar	−0.67	0.29	5.42	0.02	0.51	0.29	0.90
Elite vs. non-elite athlete	0.82	0.40	4.13	0.04	2.28	1.03	5.03
Time between injury and reconstruction [days]	0.000	0.001	0.098	0.754	1.000	0.998	1.002
Graft type: hamstring vs. quadriceps tendon	1.34	1.04	1.64	0.20	3.80	0.49	29.31

Omnibus-test: $Chi^2 = 9.8$, $p = 0.04$. Excluded variables: pandemic-associated lockdown: $p = 0.8$; sex: $p = 0.3$; Tegner activity scale: $p = 0.1$; re-injury prevention type (home-based re-injury prevention programme or usual care): $p = 0.3$.

showed faster RTS successes. Furthermore, elite athletes displayed larger exercise volumes. The larger volumes seem to be statistically more important than the elite vs. non-elite athletic status; the impact of the latter vanishes in the final model when the factors are prospectively modelled.

Considering the sample/group values of the relevant factors at the different measurement timepoints, the values of self-report knee function and readiness to RTS increase from the end of the rehabilitation over the end of the re-injury prevention to the 18-month follow-up. Afterwards, from the 18- to the 24-month follow-up, the values decrease again. Confidence to RTS is, furthermore, no longer a factor of the RTS success in the last rehabilitation stages. All participants who had successfully RTS were no longer part of the later follow-up assessments (as they had already successfully RTS). Thus, persons who had not successfully returned to their pre-injury level and type of sport up to 24 months post-reconstruction displayed a considerable low confidence to RTS.

A number of the outcomes which had an impact on RTS are modifiable. Generally, it seems to be relevant to impact modifiable factors which have a positive effect on the RTS success. Such variables could be the rehabilitation and exercise volumes or types, psychological RTS readiness, or functional capacities. These predictors, although significant when modelled together, are not independent of each other. Psychological readiness, strength and dynamic motor control capacities are also of importance to prevent a subsequent ACL injury.[10] Consequently, the improvement of one or more of these variables might decrease the re-injury risk. Both the strength and the motor control capacities can be modified by adequate (i.e., higher amounts of) exercises.[12] Improving, or even restoring, these capacities may consequently lead to a decrease in the subsequent secondary injury risk after an ACL reconstruction.[30] The functional and psychological capacities are, usually, not finally restored until after the completion of the formal, medically prescribed rehabilitation.[31] This highlights, on the one hand, the importance of continuing rehabilitation (and re-injury preventive) measures.

4.4. Practical relevance

The value of an extended re-injury preventive programme as an add-on to usual care rehabilitation is likely to be given.[28,32] Yet, this suggested value has not been finally delineated. Usually, the between group

Table 3
Determinates of a successful return to sport, derived by logistic mixed modelling. The outcome was return to sport success (no/yes); all variables included in the final model are displayed. Significant values are displayed in bold letters.

		Estimate	Estimate: 95 % confidence interval		Odds ratio	Odds ratio: 95 % confidence interval		p-value
			Lower level	Upper level		Lower level	Upper level	
Intercept		0.534	−1.985	3.054	1.706	0.137	21.2	0.676
Time since surgery [days]		−0.005	−2.889	2.878	0.995	0.056	17.7	0.997
Interaction of:	Interaction with the assessment numbers 1–4 at:							
Exercise and rehabilitation volume since last measurement	**The end of the rehabilitation**	**0.004**	**0.001**	**0.006**	**1.004**	**1.001**	**1.006**	**0.01**
	The end of the re-injury prevention	0.003	0	0.007	1.003	1	1.007	0.077
	Follow-up 18 months	0.01	−0.005	0.025	1.01	0.995	1.026	0.188
	Follow-up 24 months	$-3 \ast 10^{-7}$	$-9 \ast 10^{-5}$	$9 \ast 10^{-5}$	1	1	1	0.995
	Non-elite athlete	$3 \ast 10^{-7}$	$-9 \ast 10^{-5}$	$9 \ast 10^{-5}$	1	1	1	0.995
	Elite athlete	Reference						
Self-report knee function[a] — sport [points]	The end of the rehabilitation	−0.016	−0.039	0.008	0.984	0.961	1.008	0.185
	The end of the re-injury prevention	0	−0.035	0.035	1	0.965	1.036	0.994
	Follow-up 18 months	−0.041	−0.366	0.284	0.96	0.694	1.329	0.806
	Follow-up 24 months	$3 \ast 10^{-8}$	$-6 \ast 10^{-5}$	$6 \ast 10^{-5}$	1	1	1	0.999
Psychological readiness to return to sport[b] [points]	**The end of the rehabilitation**	**0.029**	**0.004**	**0.054**	**1.029**	**1.004**	**1.056**	**0.024**
	The end of the re-injury prevention	**0.038**	**0.004**	**0.071**	**1.038**	**1.004**	**1.073**	**0.027**
	Follow-up 18 months	0.15	−0.138	0.439	1.162	0.871	1.551	0.306
	Follow-up 24 months	$-4 \ast 10^{-8}$	$-6 \ast 10^{-5}$	$6 \ast 10^{-5}$	1	1	1	0.999
Kinesio-phobia[c] [points]	Assessment at the end of the rehabilitation	−0.052	−0.129	0.026	0.95	0.879	1.026	0.189
	The end of the re-injury prevention	0.035	−0.047	0.118	1.036	0.954	1.125	0.401
	Follow-up 18 months[d]	−0.078	−0.573	0.418	0.925	0.564	1.519	0.758
	Follow-up 24 months[d]	$1 \ast 10^{-7}$	0	0	1	1	1	0.999
Normalised knee separation distance — transition	The end of the rehabilitation	−0.012	−0.041	0.017	0.988	0.96	1.017	0.414
	The end of the re-injury prevention	**−0.04**	**−0.079**	**−0.001**	**0.961**	**0.924**	**0.999**	**0.043**
	Follow-up 18 months[d]	−0.038	−0.179	0.102	0.962	0.836	1.108	0.591
	Follow-up 24 months[d]	$-1 \ast 10^{-07}$	$-1 \ast 10^{-5}$	8E-05	1	1	1	0.998
Balance side hop — ACL side [points]	The end of the rehabilitation	−0.156	−0.555	0.243	0.856	0.574	1.275	0.442
	The end of the re-injury prevention	−0.47	−0.996	0.055	0.625	0.369	1.057	0.079
	Follow-up 18 months	−1.648	−4.486	1.191	0.193	0.011	3.29	0.254
	Follow-up 24 months	$6 \ast 10^{-7}$	−0.002	0.002	1	0.998	1.002	0.999

[a] Assessed by The Knee injury and Osteoarthritis Outcome Score (KOOS).
[b] Assessed by the ACL-RSI.
[c] Assessed by the Tampa Scale of Kinesiophobia (TSK).
[d] Values assessed at the end of the re-injury prevention.

differences found in studies aiming to compare such an extended re-injury preventive programme to usual care are small, also when the RTS success is the outcome. However, it is most likely that performing long-term, late-stage rehabilitations consisting of explosive neuromuscular performance, movement quality deficit restoration and load management may be the most promising approach when such extended re-injury preventive programmes should be performed.[33] Nonetheless, interventions beyond the initial rehabilitation period are culpably under-researched.[34]

It is recommended to perform a graduated and shared RTS process which is based on repetitive assessments of functional and psychosocial progression criteria.[18,20,21] Supported by our findings, certain functional capacities and self-reported readiness to RTS are decisive for a successful RTS. Psychological readiness can, inter alia, be affected by better functional capacities and the athlete's belief in the rehabilitation programme and the perception that their injury has healed.[35]

4.5. Strengths and limitations

In many settings and trials, RTS tests are commonly performed in one single assessment, solely at the hypothetical end of the RTS process.[18] Performing a series of measurements with the purpose of monitoring changes over time during the process of RTS may be more promising.[18] This prospective approach is a strength of our study.

There are, however, also a few limitations that must be taken into account. The data are pooled from an RCT and from a cohort trial. As half of the hamstring graft reconstructed participants (as a part of the RCT) and all quadriceps graft participants (as a part of the matching cohort) performed the specific (and not the usual care) re-injury preventive programme, this may have led to a certain interaction in the independent variables. Beyond the re-injury preventive programme, we only know the superficial training specifics and loads, but not the quality of the rehabilitation measures such as the coaching strategies; these approaches may differ between the participants. Lastly, the decision to clear an athlete, in particular an elite athlete, to RTS further considers contextual factors such as time of season, position, and level of competition. This could not be incorporated into our models.

5. Conclusion

Most important for a successful personalised return to sport after an anterior cruciate ligament reconstruction and modifiable by adequate treatments are the exercise volume, psychological readiness, and functional hop/jump abilities. By determining the factors of a successful return to sport in the two years after an anterior cruciate ligament reconstruction in a sample of mostly non-elite athletes, we found that two-thirds of the athletes returned to their previous type and level of sport. White-collar workers and elite athletes showed higher RTS rates and faster processes than blue-collar workers and than non-elite athletes. Higher volumes of exercise and rehabilitation measures were, in particular, predictive for RTS success up to the end of the rehabilitation. Until the end of the re-injury prevention period, the contribution of functional abilities increased. Psychological readiness to RTS was predictive for RTS success, both at the end of the rehabilitation and at the end of the re-injury prevention phase.

CRediT authorship contribution statement

Daniel Niederer: Conceptualization, Methodology, Software, Data curation, Writing - Original draft preparation, Visualization, Investigation. **Matthias Keller:** Methodology, Data curation, Visualization, Investigation. **Sarah Jakob, Max Wießmeier:** Data curation, Visualization, Investigation. **Wolf Petersen, Karl-Friedrich Schüttler, Turgay Efe, Natalie Mengis, Andree Ellermann, Daniel Guenther, Georg Brandl, Björn Drews, Andrea Achtnich, Raymond Best, Lucia Pinggera, Christian Schoepp, Matthias Krause:** Methodology, Data curation, Writing – review & editing. **Tobias Engeroff, David A. Groneberg:** Data curation, Writing- Original draft preparation. **Thomas Stein:** Conceptualization, Methodology, Data curation, Writing - Original draft preparation, Supervision.

Patient and public involvement

Patients were involved in the development of the intervention programme but not in the design or conduct of the study, nor in the outcome selection.

Confirmation of ethical compliance

Ethics Committee of the Hessen Regional Medical Council (reference approval no. FF 104/2017). Date of the final approval of the study protocol was June 27, 2018. All participants provided full informed written and oral consent before inclusion.

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Trial registration

German Clinical Trials Register (DRKS): registration number DRKS00015313 (01. October 2018).

Declaration of interest statement

None.

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None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2025.02.010.

Data availability

The full dataset will be made available in a public repository when all project-wide studies and planned re-analyses are published. Until then, data are available upon request.

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