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ENGINEERING **RESEARCH REPORT · Engineering research report**

Quantifying Ergonomic Improvement and Releasing Work After Deployment of a Pneumatic Industrial Manipulator

Quantitative Study of Hand Force, Posture, Cycle Time, and Work Release for a Manual Material-Handling Retrofit

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Calculation model · Test matrix · Engineering release criterion

Report structure

> Judgment rules This report uses explicit input and a unified calculation chain, and the formal judgment can only be passed or failed; failure of any hard threshold means no release.

00 Executive Summary

The nature of the task changes after deployment of a Pneumatic Industrial Manipulator, so the same metric cannot be applied mechanically before and after the change. Before deployment, the operator supports the full workpiece weight with both hands while lifting or lowering it; this is fully manual two-handed lifting and is evaluated using the NIOSH Revised Lifting Equation (RNLE), including the Recommended Weight Limit (RWL), single-task Lifting Index (LI), and multi-task Composite Lifting Index (CLI). After deployment, the manipulator supports the workpiece weight and the operator primarily applies starting, braking, pushing, pulling, steering, and positioning forces; the task is push/pull and guidance, for which RNLE does not apply. When the horizontal axis is driven entirely by the operator using both hands and whole-body effort, use a calibrated force gauge, HSE RAPP, and ISO 11228-2. When a motor, cylinder, or other power source drives the horizontal axis, RAPP does not apply; use three-axis hand-force measurement and a task-specific ergonomic assessment. Evaluate posture angles against the internal supplementary gates; assess conformity with ISO 11226 and GB/T 42730 only under each standard's complete applicability conditions.

This study establishes directly executable project release gates. Before deployment, for every remaining fully manual lifting subtask, FILI and STLI shall each be no greater than 1.00, and the CLI for all subtasks shall be no greater than 1.00. After deployment, manual load-bearing lifts during the normal cycle shall equal 0. At a mixed manual/mechanized workstation, the start/stop force for every valid cycle, corrected for resultant-force measurement uncertainty, shall be no greater than 150 N, and sustained force shall be no greater than 70 N. When RAPP is applicable, all nine official factors shall be green and the total score shall be 0; when RAPP is not applicable, a task-specific assessment shall be completed. Posture, data integrity, and residual FMEA risk shall also pass. If any condition is not met, the result is "not released"; averages, subjective impressions, or percentage improvement cannot substitute for a gate.

The results are as follows. Before deployment, two fully manual two-handed lifting subtasks with different geometries and loads have a combined frequency of 2 lifts/min; 45 min of lifting is followed by 45 min of recovery. The CLI calculated without intermediate rounding is 1.87690861858986, which exceeds 1.000000, so the condition fails. After deployment, the manipulator supports the full load and the horizontal axis has no powered drive. In the fixed 50-cycle input matrix, the maximum corrected start/stop force is 142 N and the maximum corrected sustained force is 61 N; all nine RAPP factors are green/0, and manual lifting is 0 lifts. The condition passes. Report the improvement as "manual load-bearing lifting exposure eliminated by 100%; push/pull project gates passed." Do not report post-deployment RNLE as LI = 0.

Core conclusion

1. RNLE evaluates only fully manual two-handed lifting; it does not evaluate pushing, pulling, guidance, or positioning after deployment of the manipulator.
2. If any of average mass, maximum mass, H, V, D, A, frequency, duration, recovery time, or coupling classification is missing before deployment, the RNLE calculation is invalid and the workstation shall not be released.
3. After import, the maximum resultant force of each cycle plus U_res is used to determine; only reporting the average value does not constitute acceptance evidence.

4. This report uses a lower set of HSE reference values for mixed employment as project hard thresholds: start/stop no more than 150 N, continuous no more than 70 N.
5. RAPP is only used for fully manual movements in the horizontal axis, with both hands, while standing or walking, and with steady force exerted by the whole body; RAPP is not applicable for powered horizontal axis and only upper limb control movements. The RAPP total score itself is not a universal action threshold specified by HSE; this study separately stipulates "nine factors all green, total score 0" as the item release gate for applicable actions.
6. The establishment of improvement must meet both "manual weight-bearing lifting to zero" and "all push-pull, posture, risk, and records passed after introduction." The two types of indicators cannot offset each other.

01 Research questions, action boundaries and decision logic

1.1 The two exposures must be modeled separately

Working conditions	Operator's main output	Applicable method	Prohibited practices
Fully manual two-handed lifting before deployment	Bear the entire weight of workpiece with both hands to complete lifting or putting down	RNLE：RWL、FILI、STLI、CLI；ISO 11228-1；GB/T 31002.1	Replace lift calculations with push and pull force limits
Horizontal carrying before deployment	Hold objects with both hands and walk horizontally	Portability evaluation and route evaluation of ISO 11228-1/GB/T 31002.1	Calculate only starting point RNLE and ignore carry distance
Fully manual horizontal axis after deployment	The manipulator supports the load; the operator stands or walks, holds with both hands, and uses whole-body effort to start, push/pull, steer, and stop	Triaxial force measurement, HSE push-pull reference, RAPP Section A, ISO 11228-2	Treating the manipulator's rated load as hand force
The horizontal axis has power after importing	Horizontal movement is generated by motors, cylinders, or other power sources; the operator gives control or fine positioning input	Three-axis hand force, action sequence, equipment power status and special ergonomics evaluation	Give a RAPP score or claim a RAPP pass
People and equipment share vertical loads	The operator's hands carry part of the vertical load while the assist device remains engaged	Three-axis hand-force time histories plus a task-specific biomechanical assessment; evaluate discrete fully manual segments separately with RNLE	Convert the residual hand strength to mass and then set RNLE, or record the shared load-bearing as lifting to zero

Classify the motion from the actual force-sharing condition, not the equipment name. A normal-cycle segment is push/pull or guidance only when all three conditions are met: the manipulator or tooling supports the workpiece weight in a closed load path; the operator does not use the arms to keep the workpiece from falling; and the workpiece remains controlled after hand contact is removed. If any condition is not met, the segment is shared load-bearing or fully manual lifting. An RNLE task may be defined only for a discrete motion in which the device is disengaged and the operator supports the workpiece's full weight with both hands. When the device continues to provide partial support, record RNLE as not applicable and use three-axis hand-force measurement and a task-specific biomechanical assessment.

RAPP applicability is also judged along the horizontal axis. When the horizontal drive output is 0, the operator exerts force with both hands, the body remains standing or walking, and the force acts smoothly in front of the body, RAPP Section A is used; when the horizontal drive output is not 0, the operator is sitting, operating with one hand, only controlling the upper limbs, or the action relies on external body support, the RAPP status is recorded as "not applicable", and 0 points may not be used in place of special evaluation.

1.2 release is a series system

release results are calculated by logical AND:

Release = Manual load-bearing lift gate pass AND Start/Stop force gate pass AND Sustained force gate pass AND RAPP serviceability/specialty evaluation gate pass AND Interior posture gate pass AND FMEA gate pass AND Data integrity gate pass

If any sub-gate is false, Release = not passed. Percent improvement, operator satisfaction, tempo improvement, and single cycle performance do not cover failures.

02 Standard chain, version status and adoption rules

File	Official status as of this writing	Purpose of this study
CDC/NIOSH RNLE page and DHHS 94-110	The CDC official page was reviewed online; pages 94–110 are from the 2021-09 revision.	Calculation and input rules for pre-deployment RWL, LI, and CLI
ISO 11228-1:2021	Published, second edition	Manual lifting, lowering and transfer boundaries; explicitly does not cover push and pull

File	Official status as of this writing	Purpose of this study
ISO 11228-2:2007 + Amd 1:2022	The 2007 edition and 2022 amendment have been published. The main standard is at ISO stage 90.92, and no published replacement existed as of this report's date.	Post-deployment whole-body push/pull assessment framework for motions within its scope
ISO 11226:2000	Published; reviewed and confirmed in 2018; currently in ISO 90.92 stage	Static-posture framework with no or minimal external force; angles during force application are internal supplementary gates in this report
ISO/TR 12295:2014	Published	Choose the application path of ISO 11228 series and ISO 11226
GB/T 31002.1-2014	National standard full text disclosure system indicates current	Domestic manual lifting and transfer basis; its revision project has not yet formed a replacement release version
GB/T 42730-2023	Current, implemented on 2024-03-01	Domestic static working posture evaluation basis
GB/T 36954-2018	current	Incorporating ergonomics into machinery risk assessment and risk reduction

The official name of GB/T 31054-2014 is "Terminology for Computer-Aided Engineering of Mechanical Products - Finite Element Numerical Calculation" and is not an ergonomics or manual handling standard. After verification in this study, this document was explicitly excluded and GB/T 31002.1-2014 was used instead. Similar reference numbers do not constitute a basis for standard selection.

The adoption rules are fixed as follows: international and national standards define method boundaries and assessment frameworks; CDC/NIOSH provides RNLE calculations; HSE provides push/pull reference forces and RAPP classifications; and this report converts these frameworks into stricter, auditable project release gates. The 150 N and 70 N values, all-green/0 score, 50 cycles, 100 Hz sampling rate, resultant-force uncertainty, posture angles, FMEA threshold, change-triggered reassessment, and annual cycle in this report are acceptance conditions specified by this study. This report does not interpret NIOSH, HSE, ISO, or GB/T documents as statutory occupational-exposure limits in China. HSE expressly states that values such as 150 N and 70 N are guidance values, not weight limits or approved safety limits.

03 Manual lifting baseline before import: RNLE

3.1 Required input

Each lifting subtask must record geometry at the start and end points, including at least:

symbol/field	Definition and units	Hard input rules
L_avg、L_max	Average load mass and maximum load mass of subtask, kg	Use a calibration scale to measure piece by piece; FILI uses L_max, STLI uses L_avg
H	Horizontal distance from the midpoint of the hands to the midpoint of the ankle, cm	Record the maximum measured value within the cycle; when H is less than 25 cm, it is calculated as 25 cm
V	Height of midpoint of hands above ground, cm	The starting point and end point are recorded separately
D	Vertical movement distance, cm	Less than 25 cm calculated as 25 cm
A	Asymmetrical angle between the midline of the front of the trunk and the position of the hand, °	Get the maximum value of the loop
F	Lifting frequency, times/min	Continuous observation is no less than 15 minutes; count separately according to each sub-task
Duration	Duration of continuous operation, recovery time and subsequent lifting period	For the short-duration category, continuous work shall be ≤1 h. If lifting resumes later in the same shift, the recovery-time/preceding-work-time ratio immediately following the previous work period shall be ≥1.0. If no further lifting occurs, record “no subsequent lifting in this shift.”
Coupling	good, fair or poor	Rating based on handle, container and hand contact conditions

If any fields are missing, the gauge has no valid calibration, the start and end points are not separated, or only a single posture is recorded, the RNLE record of this task will be deemed invalid and a passing conclusion cannot be issued.

The input domain is also a hard gate. H shall be no greater than 63 cm; V shall be within 0–175 cm; D shall be no greater than 175 cm; and A shall be within 0–135°. Frequency shall lie within the official FM table for the selected V and duration category. Do not extrapolate a multiplier beyond any limit; record RNLE as not applicable, and do not release the motion through RNLE. Retain the raw mass record for every item and calculate L_avg and L_max directly from those records. Geometry uses the greatest exposure in valid cycles; nominal design dimensions do not replace measurement. If the destination involves regrasping, a brief hold, precision placement, or hand guidance, retain a complete calculation chain for origin and destination and use min(RWL_origin, RWL_destination). If all four are absent, record “destination calculation not required” with the supporting determination.

3.2 RWL and LI

When using centimeters and kilograms:

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM$$

$$LC = 23\ kg$$
$$HM = \min(1,\ 25 / H)$$
$$VM = 1 - 0.003 \times |V - 75|$$
$$DM = 0.82 + 4.5 / D$$
$$AM = 1 - 0.0032 \times A$$
$$LI = L / RWL$$

Obtain FM from the official NIOSH frequency table by V, frequency, duration, and recovery condition. Obtain CM from the official coupling table. Do not interpolate linearly or assign either multiplier by experience. When a destination calculation is required, calculate RWL at the origin and destination separately and use the smaller RWL, which produces the larger LI. Acceptance always uses unrounded results; two decimal places are for display only. Any unrounded project-gate metric greater than 1.000000 fails; exactly 1.000000 is permitted.

RNLE has explicit application limits: two hands fully support a controllable load while standing in the specified industrial environment. Do not apply the equation directly to one-handed lifting, seated or kneeling work, team handling, static holding, shared load-bearing between a person and equipment, carrying while walking, pushing/pulling, shoveling, vertical motion faster than 76 cm/s, a shoe–floor static coefficient of friction below 0.4, or an unstable load. Evaluate horizontal carrying distance, frequency, and cumulative mass separately under ISO 11228-1/GB/T 31002.1. Outside the limits, do not report an approximate LI; record RNLE as not applicable and perform a task-specific assessment.

04 Multitasking CLI and Input Integrity

Whenever there are more than two loads, frequencies, geometries, grips or target heights for the same job, the subtasks must be split and the CLI must be calculated. Each subtask records L_avg and L_max respectively; first set FM to 1 to get the frequency-independent recommended weight FIRWL, and then use L_max to get FILI; get STRWL according to the frequency of each subtask, and then use L_avg to get STLI. Subtasks are sorted from high to low by unrounded STLI; when STLI is the same, the one with the greater frequency value is ranked first.

$$FIRWL_i = LC \times HM_i \times VM_i \times DM_i \times AM_i \times CM_i$$
$$FILI_i = L_{max,i} / FIRWL_i$$
$$STRWL_i = FIRWL_i \times FM_i$$
$$STLI_i = L_{avg,i} / STRWL_i$$

$$CLI = STLI_1 + \Sigma_{(i=2...n)}\ FILI_i \times [1 / FM_{(1...i)} - 1 / FM_{(1...i-1)}]$$

FM_(1...i) is the frequency multiplier corresponding to the cumulative frequency of the first i subtasks, and takes the value from the official table according to the V category, job duration and recovery conditions of the added subtask. "Average of LI across tasks" or "maximum LI"

may not be used in place of CLI. The passing conditions also include: each subtask has unrounded FILI≤1.000000, STLI≤1.000000, and the entire group has unrounded CLI≤1.000000. If the shift exceeds the duration covered by the RNLE table, the frequency exceeds the range of the table, or the cumulative frequency does not correspond to FM, the conclusion is directly "not passed RNLE release", and the blank FM cannot be regarded as 1.

Data-integrity review uses a four-eyes check: the recorder completes the raw measurements, the calculator completes equations and table lookups, and an independent reviewer checks task decomposition and units. The record is valid only when the names, dates, and version numbers of all three are present. Lock formula cells in the electronic workbook and retain inputs, table sources, and results; screenshots alone are insufficient.

05 Action decomposition and force measurement method after importing

5.1 Action segmentation

After deployment, divide a cycle into six fixed phases: approach the handle, start, steady-speed guidance, steering/height adjustment, stop/fine positioning, and disengagement. Evaluate peak force during start and stop; sustained force during steady-speed guidance, steering, and height adjustment; and posture plus absence of unintended manual load support during approach and disengagement. Between tooling clamp and workpiece release, cumulative manual-support time shall be 0 s and the number of manual load-bearing lifts shall be 0.

5.2 Instrumentation and calculations

Use a three-axis force gauge with a single-axis range of at least ±500 N, a resolution of no greater than 1 N, a sampling frequency of no less than 100 Hz, and a valid calibration period of no more than 12 months. The coordinates are fixed as: Fx along the movement direction, Fy for the horizontal and transverse direction, and Fz for the vertical direction. The sensor is installed between the actual handle and the force path of the hand and must not change the handle height, grip distance or movement resistance. Clear before and after each group of tests; when the absolute value of the zero point difference of any axis is greater than 2 N, the data of this group will be invalidated and the entire group will be retested.

The resultant expanded uncertainty is defined as U_res and the single-axis expanded uncertainty in the calibration certificate is not added directly. Divide the expanded uncertainty of each axis k=2 by 2 to obtain the standard uncertainties u_x, u_y, u_z, and add the standard uncertainties of the zero point, installation angle and repeatability:

$$\mathrm{Fres}(t) = \sqrt{[\mathrm{Fx}(t)^2 + \mathrm{Fy}(t)^2 + \mathrm{Fz}(t)^2]}\, u\_res^2 = (Fx/Fres)^2 u\_x^2 + (Fy/Fres)^2 u\_y^2 + (Fz/Fres)^2 u\_z^2 + u\_zero^2 + u\_align^2 + u\_repeat^2 U\_res = 2u\_resFstart,c = \max(\text{in the start window and stop window Fres}) + U\_res,startFsus,c = \max(\text{average Fres of any continuous 1.0 s within the constant speed and steering window}) + U\_res,sus$$

U_res takes the calculated maximum value within each determination window and must not be greater than 5 N. If Fres=0, the directional derivative term is set to 0, and only the zero point, installation angle and repeatability terms are retained. If the guidance window is shorter than 1.0 s, Fsus,c takes the average of all sampling points in the window and adds U_res,sus. The start window starts from when Fres exceeds 10 N for the first time until the speed remains within ±5% of the set speed for 0.5 s continuously; the stop window is from 1.0 s before reaching the target until the speed is 0 for 0.5 s continuously. Video, motion signals and force measurement signals must be synchronized within 0.1 s. The reported value is always "indication value + U_res", and uncertainty must not be added after the threshold value is judged.

The HSE guideline requires that the minimum push-pull force required to start the load is compared with the guideline value; this study instead uses the actual maximum three-axis resultant force in normal operation and adds U_res, which is a more stringent internal exposure door and is not equivalent to the HSE original measurement method. 150 N and 70 N are only used as numerical gates for this study and are not legal limits.

5.3 Test coverage

For each design boundary condition, use 5 qualified operators from the actual job, each completing 10 consecutive full cycles, for 50 valid cycles total. The sample shall include the shortest and tallest individuals on the job roster; record the heights of all 5 operators in whole centimeters. If women work in the job, at least 2 of the 5 operators shall be women. Boundary conditions shall cover at least maximum rated workpiece mass, maximum working radius, minimum and maximum permitted handle heights, both travel directions, and the lowest permitted air-supply pressure or power state. Complete 50 cycles independently for each boundary condition; do not combine conditions.

The hard passing condition is that every valid loop satisfies:

$$F_{start,c} \le 150\ \text{N}$$
$$F_{sus,c} \le 70\ \text{N}$$

The values of 150 N and 70 N are taken from HSE guidance values for women and serve as thresholds for mixed employment projects. If any valid cycle exceeds the limit, the judgment will be failed, and the judgment cannot be changed by averaging, P95 or deleting the person who exceeded the limit. The upper limit of the one-sided 95% binomial distribution failure rate corresponding to 50/50 zero failure is 1−0.05^(1/50)=5.82%.

06 RAPP, route and static posture evaluation

First determine whether RAPP applies. Use RAPP Section A when the horizontal axis has no powered output and the operator, standing or walking and using both hands and whole-body effort, moves overhead-rail or wheeled equipment smoothly. If the horizontal axis has powered output, the motion is performed only by the upper limbs, operation is one-handed or seated, or the person relies on external body support, record RAPP as not applicable and use three-axis

hand-force measurement plus a task-specific ergonomic assessment. The work shall not be released until that assessment is complete; a RAPP score of 0 cannot substitute for it.

For applicable actions, HSE RAPP uses color to indicate risk: green is low risk, amber is medium risk, red is high or very high risk, and purple is unacceptable. The HSE also explains that the overall score is used for comparison and prioritization purposes and is not a universal action threshold. In order to avoid total score offset, this study stipulates that the nine factors A-1 to A-9 must be green and scored 0 points, and the total score must be 0; any amber, red or purple factors will be judged as failed.

Evaluation object	This study release value	Live evidence
torso	During the force action stage, forward flexion ≤20° and axial rotation ≤10°	Side and top view synchronized video or angle sensors
hand height	The start, lead and stop phases are all located between the hip and the shoulder	Video frame of ruler background
grasp	Grip the hands completely; the absolute value of wrist flexion and extension is ≤15°, the absolute value of radioulnar deviation is ≤10°; RAPP grip factor green/0	Handle size, front and side videos and angle records
Lower limbs	The duration of kneeling, squatting, and pushing with your back is 0 s.	full loop video
Operation mode	No sudden impact, no one-hand swing, no body relying on gravity to start.	Video and force curve
Device status	Brakes, bearings, tracks, hoses/cables are all intact and no binding	inspection record before class
Ground and routes	Dry, level, no steps, no tripping objects, and clear passages that meet the work location plan	Dated photos and route checklist

Forward flexion 20°, rotation 10°, wrist flexion/extension 15°, and radial/ulnar deviation 10° are internal supplementary gates in this study. Evaluate force-phase angles against these gates; assess conformity with ISO 11226 and GB/T 42730 only under each standard's complete applicability conditions. Use the maximum absolute angle over the full cycle, not a cycle-average angle. Equipment rated capacity is a separate hard gate: maximum workpiece mass shall not exceed the lowest rating among the equipment, end-effector tooling, lifting points, and connectors. When RAPP applies, exceeding an equipment rating is purple/unacceptable and requires an immediate stop.

07 Test design, data quality and traceability records

The release package must contain the following original materials. If one is missing, the data gate will fail:

1. Measured mass of every workpiece, L_avg, L_max, center-of-mass range, gripping points, workstation cycle time, and shift duration;
2. Original table of H, V, D, A, F, duration, recovery time, destination control determination and grip level for each subtask before import;
3. Rated capacities and allowable pressure/voltage ranges of the manipulator, tooling, lifting points and connections;
4. Dynamometer serial number, calibration certificate, u_x/u_y/u_z, u_zero, u_align, u_repeat, U_res, sampling rate, installation photos and zeroing records;
5. Operator anonymous number, height range, job qualifications and test conditions;
6. The original three-axis timing, segment markers, unrounded Fstart,c, unrounded Fsus,c for each cycle must not only save the summary value;
7. Full cycle synchronized video, RAPP applicability determination, A-1 to A-9 factor table when applicable, special evaluation records, posture angle records and route photos;
8. RNLE calculation sheets, FMEA, deviation records, review signatures, software/form versions and final judgment.

Invalid cycles are only allowed to be eliminated due to instrument disconnection, synchronization failure, or clear non-process external interruptions. The reasons must be recorded at the test site; they cannot be eliminated because the force value is too large, the movement is not smooth, or the operator's posture is poor. After elimination, it must be reworked until 50 valid cycles are obtained for each boundary condition. Preserve all invalid original files and reasons to prevent selective reporting.

Fix equipment warm-up and test conditions: complete startup checks as specified by the manufacturer; record air pressure, voltage, lubrication, braking, and load state; use the maximum workpiece mass in the design envelope; and do not increase assistance settings before formal testing. Record parameter values, software version, balance setting, and speed setting in the configuration baseline. Export them again after the test for comparison; any difference invalidates the test set.

08 Manual lifting calculation before import

The fixed inputs for this chapter define two fully manual two-handed lifting subtasks that differ in load, H, V, D, A, and coupling classification. Each occurs at 1 lift/min, for a total of 2 lifts/min. After 45 min of continuous lifting, provide 45 min of seated monitoring work; recovery time/work time = 1.0. No new lifting period begins afterward, so use short-duration FM. For both subtasks, regrasping, holding, precision placement, and hand guidance at the destination are all absent, so calculate only at the origin.

input	Subtask A	Subtask B
L_avg	18.0 kg	12.0 kg
L_max	18.0 kg	14.0 kg
H	40 cm	35 cm
V	50 cm	80 cm
D	50 cm	40 cm
A	30°	15°
grasp	Average	good
Frequency	1 time/min	1 time/min
duration/recovery	45 min/45 min	45 min/45 min

8.1 Multipliers and single-task results

Subtask A: HM_A = 25 / 40 = 0.6250000VM_A = 1 - 0.003 × |50 - 75| = 0.9250000DM_A = 0.82 + 4.5 / 50 = 0.9100000AM_A = 1 - 0.0032 × 30 = 0.9040000CM_A = 0.9500000FIRWL_A = 23 × 0.625 × 0.925 × 0.910 × 0.904 × 0.95 = 10.3916141875 kgFILI_A = L_max,A / FIRWL_A = 18 / 10.3916141875 = 1.73216592487162FM_A (1 time/min, short time, V＜75 cm) = 0.94STRWL_A = 10.3916141875 × 0.94 = 9.76811733625 kgSTLI_A = L_avg,A / STRWL_A = 18 / 9.76811733625 = 1.84272970731024 Subtask B: HM_B = 25 / 35 = 5 / 7 (displayed as 0.714285714285714) VM_B = 1 - 0.003 × |80 - 75| = 0.9850000DM_B = 0.82 + 4.5 / 40 = 0.9325000AM_B = 1 - 0.0032 × 15 = 0.9520000CM_B = 1.0000000FIRWL_B = 23 × (5 / 7) × 0.985 × 0.9325 × 0.952 × 1 = 14.3655355 kgFILI_B = L_max,B / FIRWL_B = 14 / 14.3655355 = 0.974554690286345FM_B (1 time/min, short time, V≥75 cm) = 0.94STRWL_B = 14.3655355 × 0.94 = 13.5036034 kgSTLI_B = L_avg,B / STRWL_B = 12 / 13.50360337 = 0.888651693270224

The above multipliers are calculated exactly as entered, and the calculation chain is back-calculated without using the displayed digits; the threshold determinations for FIRWL, FILI, STRWL, STLI, and CLI use the complete values in the spreadsheet. In unrounded STLI order, subtask A is ranked first and subtask B is ranked second. A's FILI and STLI both exceed 1.000000, and the single-task project gate has failed; B's FILI and STLI have both passed.

8.2 Composite task CLI

After adding subtask B, the cumulative frequency is 2 times/min. The CLI incremental item must be looked up in the table according to the V category of the added subtask B: when short-term and V≥75 cm, the previous cumulative frequency ΣF_A=1 times/min corresponds to FM_B(ΣF_A)=0.94. After adding B, Σ(F_A+F_B)=2 times/min corresponds to FM_B[Σ(F_A+F_B)]=0.91:

```
CLI = STLI_A + FILI_B × {1 / FM_B[Σ(F_A+F_B)] - 1 / FM_B(ΣF_A)}
                      = 1.84272970731024
            + 0.974554690286345 × (1 / 0.91 - 1 / 0.94)
                      = 1.87690861858986
```

indicator	Calculated value	release value	Judgment
Subtask A FILI	1.73216592487162	≤1.000000	failed
Subtask A STLI	1.84272970731024	≤1.000000	failed
Subtask B FILI	0.974554690286345	≤1.000000	Pass
Subtask B STLI	0.888651693270224	≤1.000000	Pass
Two-task CLI	1.87690861858986	≤1.000000	failed
Manual weight-bearing lifting frequency	2 times/min	Baseline records before importing	Quantified

Pre-deployment deterministic conclusion: the CLI calculated without intermediate rounding is 1.87690861858986, and both FILI and STLI for subtask A exceed their limits; this calculation condition fails the manual-lifting release criteria. It is incorrect to declare the task safe because

“18 kg is below 23 kg,” because 23 kg is only the load constant. The geometry, asymmetry, frequency, and coupling of subtask A reduce STRWL to 9.76811733625 kg.

09 Push, pull and guide calculation after import

Workpiece mass remains 18 kg. Throughout the normal cycle, the manipulator and tooling independently support the workpiece weight; manual support time is 0 s and manual load-bearing lifting frequency is 0 lifts/min. The equipment supports the vertical axis, and horizontal-axis drive output is fixed at 0. The operator stands or walks, keeps both hands on the handle, and uses whole-body effort for starting, 2 m of horizontal guidance, steering, stopping, and positioning. This motion therefore meets the RAPP Section A applicability conditions in this report; RNLE is not calculated.

This chapter uses the maximum value of 10 cycles for each person as the calculation input; the U_res of each result is 3 N, and the correction value is equal to the maximum input value plus 3 N.

Personnel group	Personnel conditions	Enter start/stop maximum value N	Corrected starting/stopping force N	Enter the maximum sustaining force N	Modified Sustainability N	10 cycle judgment
O1	152 cm/male	115	118	39	42	10/10 passed
O2	160 cm/female	123	126	44	47	10/10 passed
O3	168 cm/male	128	131	48	51	10/10 passed
O4	172 cm/female	134	137	52	55	10/10 passed
O5	185 cm/male	139	142	58	61	10/10 passed

The corrected maximum values in 50 cycles are 142 N and 61 N:

Start/stop force margin = (150 - 142) / 150 × 100% = 5.33333333333333% Sustained force margin = (70 - 61) / 70 × 100% = 12.8571428571429% Manual weight-bearing lifting elimination rate = (2 times/min - 0 times/min) / 2 times/min × 100% = 100%

The RAPP calculation uses Section A's nine official factors. The moving part of the large overhead track and end-effector tooling total 22 kg. After adding 18 kg workpiece, the estimated moving mass is 40 kg; the allowed moving mass of the equipment is 60 kg.

RAPP Section A Factor	Evaluation input	Score/Judgment
A-1 Equipment type/load mass	Large overhead track equipment; moving mass 40 kg＜600 kg and ≤60 kg allowed value	green/0
A-2 posture	Trunk forward flexion up to 16° and rotation up to 7°; hands always between hips and shoulders	green/0
A-3 Hand Grip	Full power grip with both hands; wrist flexion and extension up to 12°, radioulnar deviation up to 8°	green/0
A-4 Operation Mode	2 transfers/min < 5 transfers/min; operator starts each transfer independently	green/0
A-5 moving distance	2 m≤10 m each time	green/0
A-6 Equipment status	Monthly preventive maintenance plan is in effect; pre-test brake, track, bearing and hose function checks all passed	green/0
A-7 Ground	Epoxy floor, slope 0°, dry, clean, solid and undamaged	green/0
A-8 Route Obstacles	0 each of trailing cables, raised edges, ramps, steps, closed or narrow doors, screens or confined spaces, route corners and fixed obstacles; changes of direction are completed within a 2 m open area	green/0
A-9 Other factors	Equipment and load instability, blocked line of sight, sharp/high temperature contact surfaces, insufficient lighting, gusty winds or strong air currents, PPE or clothing hindering operation, 0 items each; illumination 500 lx, temperature 22°C, relative humidity 45%, indoor wind speed 0 m/s	green/0
total	A-1 to A-9 are all green	0

release item	Result	threshold	Judgment
Manual weight-bearing lifting	0 times/min	Must be 0 times/min	Pass
RNLE	Not applicable	Not allowed to be used for push and pull	The method is correct
RAPP applicability	Horizontal axis without power, hands, standing/walking, whole body force application	Four items must be met at the same time	Pass
Corrected start/stop force	142 N	≤150 N	Pass
Corrected Sustainability	61 N	≤70 N	Pass
RAPP	A-1 to A-9 are all green, 0 points	Nine factors are all green, 0 points	Pass
interior posture door	16° of forward flexion, 7° of rotation, 12° of wrist flexion and extension, and 8° of radioulnar deviation.	≤20°、≤10°、≤15°、≤10°	Pass

Post-deployment conclusion: under the fixed calculation inputs and 50-cycle summary data in this chapter, all project gates pass and the operating condition is released. Zero failures in 50/50 cycles is a deterministic project-sample acceptance result; interpret the population failure rate using the statistical upper bound in Section 5.3. The correct improvement statement is: “manual load-bearing lifting frequency decreased from 2 lifts/min to 0 lifts/min, a 100% elimination; the post-deployment push/pull-force and RAPP project gates passed.” Incorrect statements include “CLI decreased from 1.87690861858986 to 0” and “LI improved by 100%,” because RNLE is not applicable after deployment; it is not zero.

10 Improve quantification, release standards and conclusion templates

10.1 Quantitative indicators

Improvement reports must be presented side by side without combining different dimensions into a single score:

Manual lift elimination rate = (number of manual lifts before introduction - number of manual lifts after

introduction) / number of manual lifts before introduction × 100% starting force margin = (150 - maximum corrected start/stop force) / 150 × 100% sustained force margin = (70 - maximum corrected sustained force) / 70 × 100%

When there are still discrete complete manual lifts after import, the FILI, STLI, and CLI must be recalculated for the task, and the residual lifting frequency is reported; at this time, the elimination rate of manual lifts is less than 100%, and "complete elimination" cannot be written. RNLE is not calculated when the person and equipment share the load, and three-axis hand strength and special biomechanical evaluation are used instead. A force margin less than 0 means failure. A positive margin only indicates passing the threshold and is not equivalent to the product's rated capacity or safety factor.

10.2 One vote to veto the release table

No.	release project	pass conditions	Fail condition
G1	method boundaries	Use RNLE for fully manual two-handed lifting; use three-axis hand force and a task-specific assessment for shared load-bearing; route push/pull assessment according to horizontal-axis powered state	RNLE for shared load bearing/push-pull, or powered horizontal axis to give RAPP score
G2	Residual manual lifting	Each unrounded FILI, STLI ≤ 1.000000 and CLI ≤ 1.000000; if full assist is declared, normal cycle lifting frequency = 0 times/min	Any FILI/STLI/CLI exceeds the limit, or there is still manual support
G3	start/stop force	All valid cycles Fstart,c≤150 N	Any cycle＞150 N
G4	Sustainability	All valid cycles Fsus,c≤70 N	Any cycle＞70 N
G5	RAPP/Special Evaluation	When RAPP is applicable, A-1 to A-9 are all green/0; when RAPP is not applicable, the special evaluation is completed and passed	The applicability judgment is wrong, any RAPP factor is not green, or the special evaluation is missing/failed
G6	interior posture door	Forward flexion ≤20°, rotation ≤10°, wrist flexion and extension ≤15°, radioulnar deviation ≤10°, hand between hip and shoulder, kneeling/squatting/back push=0 s	Any item exceeds the limit

No.	release project	pass conditions	Fail condition
G7	Rated capacity	workpiece quality does not exceed the minimum rated capacity of the entire chain	Overload or missing rated data
G8	data	5 people x 10 cycles per boundary condition; original triaxial forces, U_res, video, calibration and configuration complete; use unrounded values for judgment	Missing samples, boundaries, raw timing, uncertainty, or records
G9	risk	All residual RPN＜20; S=5 items have two independent controls	RPN≥20, or S=5 only one control

Standard conclusions can only use the following two sentence patterns:

- Passed: "Within the listed design boundaries, G1 ~ G9 are all satisfied, working condition release; if it exceeds the boundary, it must be re-evaluated."
- Failure: "G [number] is not satisfied, and the working conditions are not release; you can reapply for release only after completing the correction and retesting according to the complete plan."

There are only two official judgment states: "pass" and "fail", and the third state is not allowed to be output.

11 Risk Analysis and FMEA

This study uses levels 1 to 5 of severity S, occurrence degree O, and detection degree D, and RPN=S×O×D. The project gate stipulates that the residual RPN must be less than 20; even if the RPN of a failure with severity S=5 is less than 20, it must have two independent controls, one for prevention and one for detection or isolation. The scoring definition is fixed as follows:

Points	Severity S	Occurrence degree O	Detection D
1	No personal injury, shutdown ≤15 minutes	The failure path has been eliminated by the structure, or two independent controls must fail simultaneously.	Safety functions automatically block actions before personnel are exposed, providing that all fault injections pass
2	Only on-site first aid required, no lost working days	Occurs when one monitored control fails and another independent control is bypassed	Automatically detect and safely isolate within the current cycle

Points	Severity S	Occurrence degree O	Detection D
3	Requires medical treatment or loses 1 to 3 days of working days	A single hardware, software or operating error can trigger	It can be detected by pre-shift or fixed period inspection, but not automatically detected during operation.
4	Hospitalization, permanent partial loss of function, or loss of working days > 3 days	There is a measurable degradation path within the prescribed maintenance cycle	Can only be detected through sound, resistance or posture changes observed by the operator
5	Death, permanent total loss of functionality, or loss of control of suspended loads	This state exists in every normal cycle	No detection method or detection occurs after injury

O or D are only allowed to be reduced if control structures, test records and review signatures are present; in the absence of evidence of any of these, the initial score is used. The table below calculates the initial risk, controls, and residual risk for an FMEA based on fixed inputs.

failure mode	Consequences	Initial S/O/D/RPN	fixed control	O/D reduction conditions	Residual S/O/D/RPN	Conclusion
Use the RNLE for shared load bearing or push and pull applications	Wrong risk assessment method	4/3/4/48	Method decision table + independent review	E1: 50/50 records must complete method identification and double signatures	4/1/3/12	Pass
Maximum radius or minimum pressure not covered	The actual force exceeds the test value	5/3/4/60	Boundary matrix prevention + parameter locking/log detection	E2: All boundaries must complete 50 cycles each; 10/10 cross-border parameters must be automatically locked	5/1/2/10	Pass

failure mode	Consequences	Initial S/O/D/RPN	fixed control	O/D reduction conditions	Residual S/O/D/RPN	Conclusion
Only look at the average force and miss the starting peak value	Short-term overload not recognized	4/3/4/48	100 Hz raw timing + cycle-by-cycle maximum plus U_res	E3: 10 groups of peak injections must be retained by the algorithm and judged as over-limit in the acceptance review	4/1/3/12	Pass
The position of the handle causes the torso or wrist to cross the line	Increased exposure of shoulders, back or wrists	4/3/3/36	Hip and shoulder height mechanical limit + angle video review	E4: The 50/50 cycle limit must be valid; the angle record must be reviewed cycle by cycle	4/1/3/12	Pass
Track, brake or hose added resistance	The starting force exceeds the limit or the load is out of control	5/2/4/40	Mechanical force limiting/maintenance prevention + pre-shift functional inspection and detection	E5: 10/10 times of resistance-increasing injection must be limited; 30/30 times of setting faults must be detected by pre-shift inspection	5/1/2/10	Pass
Changes in parameters or workpiece have not been re-evaluated.	Original release boundary invalid	4/3/4/48	Controlled recipe + change approval interlock	E6: 10/10 unauthorized changes must be locked and a log kept	4/1/2/8	Pass

failure mode	Consequences	Initial S/O/D/RPN	fixed control	O/D reduction conditions	Residual S/O/D/RPN	Conclusion
Operator sample does not cover roster height boundaries	Personnel exceeding the height limit	3/3/4/36	The person with the smallest/largest height included in the roster + a hard goal	E7: The five personnel conditions of 152, 160, 168, 172, and 185 cm must complete 10 cycles each and record them completely.	3/1/3/9	Pass

E1~E7 are O/D reduction conditions. If the corresponding records are complete and reviewed, the residual score in the table will be used; otherwise, the initial score will be used. FMEA, force measurement, and RNLE together constitute the release evidence. When any failure mode control changes, recalculate the residual risk and execute G1 to G9 completely; do not modify only the RPN number.

12 Change control, periodic review and operating documents

If any of the following trigger conditions occurs, the original release will immediately become invalid and G1~G9 will be completely redone:

1. The mass of workpiece exceeds the maximum value of release, or the center of mass exceeds the three-dimensional envelope of release;
2. The working radius, handle height, moving distance, speed or acceleration exceeds the minimum-maximum range frozen in the test;
3. Cycle frequency, continuous operation duration, recovery time or shift structure exceeds RNLE/RAPP release input;
4. Changes to the manipulator, tooling, lifting points, handles, brakes, tracks, hoses, cables, air pressure, voltage, speed or control recipe;
5. Add new slopes, steps, corners, slippery sources or obstacles to the route;
6. An uncontrolled fall, collision, clamping failure, starting force exceeding the limit, sustaining force exceeding the limit, or ergonomic injury occurs;
7. Dynamometer calibration fails, raw data is lost, or calculation formula/task splitting errors are discovered.

There are no re-evaluation exemption percentages or dimensional tolerances. Any value that exceeds the freeze boundary by even 1 minimum recording unit immediately cancels the

release; 5%, 50 mm, 100 mm or 10% shall not be used as an exemption outside the release boundary.

Even if there are no changes, equipment, tooling, brakes, tracks and routes inspection must be completed before the shift; 50 cycles of the boundary conditions that produce the maximum Fstart,c or Fsus,c in the frozen matrix must be retested annually, and RAPP, posture records and FMEA must be updated. The annual cycle is calculated from the official release signing date. If the retest is not completed for more than 12 months, the workstation status will automatically change to "Not release".

The on-site standard work instruction shall state maximum workpiece mass, permitted working radius, handle-height range, permitted pressure/voltage, speed recipe, normal motion sequence, prohibition of manual lifting, abnormal-stop procedure, and pre-shift inspection items. A training record proves only that training occurred; it does not establish competence. An operator becomes qualified for the job only after completing 10 consecutive cycles under controlled conditions with every force and posture gate satisfied.

13 Research conclusions

The ergonomic value of a Pneumatic Industrial Manipulator cannot be demonstrated solely by showing that the manipulator lifts the load. An effective quantitative path is to establish the pre-deployment RWL, FILI, STLI, and CLI baseline for fully manual two-handed lifting using RNLE, then confirm whether post-deployment manual load-bearing has fallen to zero. Shared load-bearing is evaluated using three-axis hand force and a task-specific biomechanical assessment. For fully assisted push/pull, measure start/stop peak force and sustained force in every cycle and select RAPP or a task-specific assessment according to the horizontal-axis powered state. Finally, place the internal posture gates, rated capacity, data integrity, and FMEA in series for release.

This report expresses method boundaries and acceptance as hard gates: unrounded RNLE FILI, STLI, and CLI are each ≤1.000000; post-deployment manual load-bearing lifting is 0 lifts/min; corrected resultant start/stop force including U_res is ≤150 N in every cycle; corrected sustained resultant force including U_res is ≤70 N; when RAPP applies, all nine factors are green and the total is 0, and when it does not apply, the task-specific assessment passes; internal posture gates require forward flexion ≤20°, rotation ≤10°, wrist flexion/extension ≤15°, and radial/ulnar deviation ≤10°; residual RPN is <20; and the evidence package is complete. Failure of any item means not released.

The deterministic results are: before deployment, subtask A has FILI=1.73216592487162 and STLI=1.84272970731024, while the two-task CLI=1.87690861858986; the condition fails. After deployment, manual lifting is eliminated by 100%, maximum corrected start/stop force is 142 N, maximum corrected sustained force is 61 N, and all nine RAPP factors are green with a total score of 0; all gates pass. These results apply only to the operating conditions and calculation inputs listed in this report. Interpret the population failure rate using the one-sided 95% upper bound in Section 5.3. The formal conclusion reports only pass or fail.

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