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Hauling stone blocks for pyramid construction by use of block-and-tackle systems

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1 Heavy-duty transportation in ancient Egypt

Egyptologists, physicists, and civil engineers alike are interested in the question of how the ancient Egyptians transported and lifted statues, obelisks, and stone blocks weighing tons, even in the Old Kingdom.

1.1 Pictorial and textual evidence

Wall reliefs from elite tombs depict inscribed scenes showing larger-than-life statues being hauled on sledges.[1] In these scenes, a man is shown pouring a liquid onto the ground in front of the sledge (Fig. 1, 2). In the Old Kingdom tomb of Ti, the text immediately above this man reads *stj.t ꜥḏ mw jn ẖrp jz.t n pr-ḏt*, which may be translated as “pouring out oil and water by the overseer of the workmen's crew of the funeral foundation”. However, the word contraction of *stj.t* and *ꜥḏ* at the beginning of the sentence suggests that *stj.t-ꜥḏ* was a technical term meaning “pouring out for the purpose of lubrication”, even if pure water was poured out. Experiments have shown that the carefully dosed moistening of a sand track (4–5 vol% water[2]) compared to dry sand reduces the force required to set a loaded sledge in motion and maintain a constant speed by up to 70% and 40%, respectively.[3] It is unlikely that vegetable oil was added to the water because it was not produced on a large scale in Egypt at that time, so it would have been too valuable to pour out.[4] Alternatively, the track could have been covered with fine clay mud which was kept moist.[5] In comparable Assyrian reliefs, one can see planks being laid lengthwise in front of the sledge.[6] However, the reliefs in the tombs of Ti and Djehutihotep (Fig. 1, 2) neither depict nor mention planks.[7] Numerous spheres made of dolerite or diorite that were found near the Aswan and Gebel el-Ahmar quarries have been interpreted as aids to

1 Tomb of Ti (Ref 1, plt 55); tomb of Djehutihotep (Ref 2, plt 12). The Egyptian Museum Cairo keeps a sledge from the Middle Kingdom (CG 4928).

2 Ref 3, pp. 2 (fig 2), 3 (fig 5); Ref 4, fig. 3.

3 Ref 3, pp 3, 4. These and similar experiments put an end to the academic debate about whether pouring water in front of the sledge served a ritual or technical purpose (Ref 5, pp 45–46).

4 Ref 6, p 64; Ref 7, p 14; Ref 8, pp 41–44.

5 Ref 9, p 47; Ref 10, pp 62–73; Ref 11, pp 18–20, figs 14–16.

6 Relief fragment BM 124822; Ref 6, p 63, figs 5, 6 (after Layard); Ref 7, pp 12–13, 15 (fig 1). The timbers' orientation parallel to the track, as depicted, indicates that they were planks or wooden rails (Ref 13, p 273), not "rollers" (Ref 12, p 106).

7 Below the colossus in Djehutihotep's relief, there are three men carrying a timber. This has been interpreted as a slipway timber (Ref 6, pp 60 [no. 14], 62; Ref 14, p 18). However, the accompanying text says “carrying timbers for the altars” (*fꜣj.t ẖt.w n stꜣ jn ẖꜣ.wt*). C. Davison postulated "lubricated boards" (Ref 7, p 16). As for the wooden rollers that are sometimes suggested, they have been proven to be unsuitable through experimental testing (Ref. 13, p 268).

reduce the sliding friction of sledges.[8] Oxen were also employed to pull the sledges.[9]

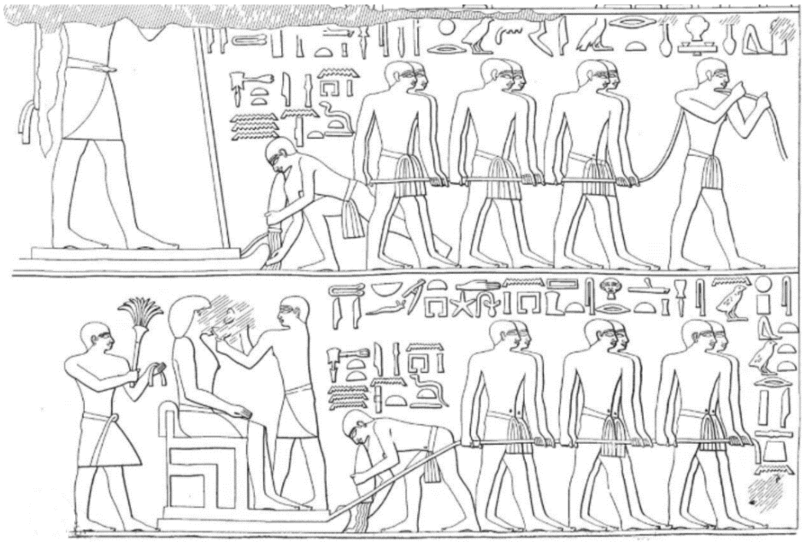

Fig. 1: Statue transportation, tomb of Ti, 5th Dyn., Saqqara

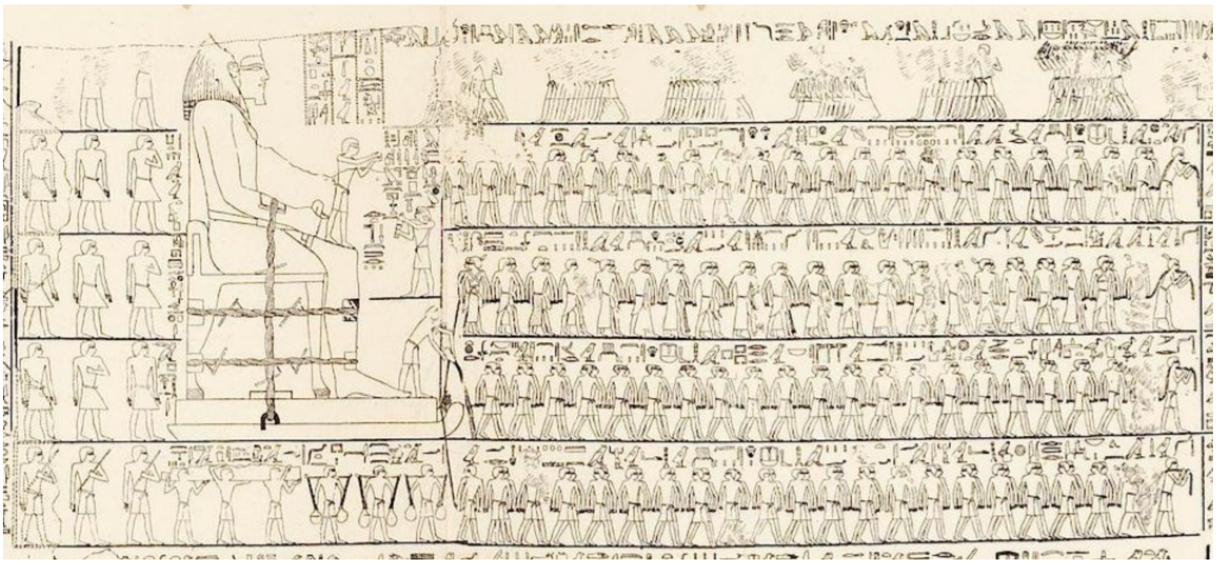

Fig. 2: Statue transportation, tomb of Djehutihotep, 12th Dyn., Deir el-Bersheh

8 Making use of the rolling friction, similar to contemporary ball bearings. Literature review in Ref 15, pp 50–51.

9 Tomb of Hetepherakhti (5th Dyn.), Ref 15, p 53, fig 4.3.3.4; coffin of Ibet (12th Dyn.), Université de Lille III, Institut de Papyrologie et d'Égyptologie, inventory number L 1653; wall painting in the quarry of Ma'asara (18th Dyn.), Ref 16, p. 306, fig 453; Ref 17, plt III. Ti and Djehutihotep likely relished flaunting their opulence through a considerable workforce.

1.2 Ramps for pyramid construction

It is reasonable to assume that the transportation of limestone blocks from the quarry to the quay[10] and from the quay to the construction site was accomplished using sledges.[11] However, it is unclear how the blocks were placed in the masonry, as there is no pictorial or textual evidence. The most popular explanations involve construction ramps of various designs built adjacent to, around, or within the growing pyramid.[12]

Even though such ramps are controversial,[13] I believe they were necessary. Lifting heavy loads[14] vertically to a height of over 140 meters, or pulling them up the steep pyramid flank, is inconceivable without modern machinery. This is true even when the traction ropes are guided over rollers at the upper edges of the growing structure.[15] Conversely, on a flatter ramp, the necessary traction force is reduced at the expense of a longer path (a force/distance tradeoff). Ramps made of unfired mud bricks can bear a sufficient load.[16] Remains of brick ramps have been discovered near several pyramids of the Old and Middle Kingdoms.[17]

2 Hypothesis: Stone blocks were hauled using block-and-tackle systems

Assuming the reliefs shown in Figures 1 and 2 represent the transportation process realistically,[18] the Egyptians relied on combined human muscle power. However, the brick ramps that various authors claim were built adjacent to pyramids[19] lacked the space for 32 or more workmen.[20] The ramps would have had to be so wide that constructing them

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10 Unlike limestone from Turah for the casing blocks and granite from Aswan, the limestone for the core blocks came from local quarries (Ref 18, pp 15–18; Ref 19, pp 109–129).

11 The area around some pyramids still has traces of transportation paths (Ref 18, pp 15–18; Ref 20, pp 380 (fig 1), 382; Ref 19, p 121; Ref 7, p 11 [quoting Layard]; Ref 21, pp 1–2).

12 Ref 19, pp 129–132; Ref 18, pp 20–24; literature reviews in Ref 22; Ref 23, pp 5–7.

13 Summary of drawbacks in Ref 22.

14 The limestone blocks of the core masonry weighed 2.5 tons on average, the pyramidion weighed up to 7 tons, the granite sarcophagi weighed up to 40 tons, and the vault stones of the King's Chamber weighed up to 80 tons (Ref 18, p 20 [note 19]; Ref 22; Ref 24).

15 E.g. Ref 25.

16 Ref 26, pp 282–284.; Ref 27. From the reign of Senwosret II onwards, mud bricks were also used for the pyramid core (Ref 15, pp 14, 99–100).

17 Literature review in Ref 15, pp 41–47.

18 The haulers' upright walking posture raises doubts (work postures were otherwise depicted relatively realistically). The remains of the 13-cubit (6.8 m) high colossal statue of Djehutihotep have never been found.

19 Ref 22.

20 de Haan's calculations indicate that at least 32 workmen were needed to pull a 2.5-ton stone block up a ramp (Ref 23, p 18). The number of haulers in the tomb relief of Djehutihotep is 172 (Ref 6, pp 58, 68; Ref 28, p 470).

would have required more space, manpower, and time than building the pyramid itself.[21] This leaves no other conclusion than that the Egyptians were familiar with the block-and-tackle technique.[22]

2.1 The principle of a block and tackle

A block and tackle can shift the force/distance tradeoff further toward distance than a ramp can. This is achieved through the length of the traction rope, which is guided over fixed and movable rollers or sheaves (pulleys). The traction force (F in newtons) required for vertical lifting of a given load can be calculated using the formula $F = \frac{F_W}{N_{rs}}$ where F_W is the weight force of the load in newtons (approximately equal to the weight in kilograms multiplied by 10) and N_{rs} is the number of rope segments between the fixed and movable elements (see Fig. 3).

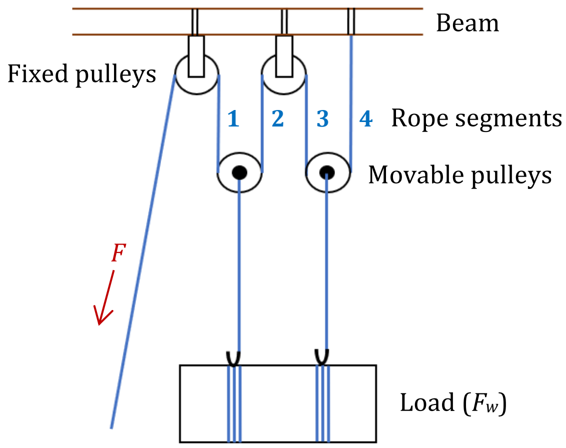

Fig. 3: Schematic of a block and tackle with 2 movable pulleys ($F = F_W/4$)

It is beyond doubt that the ancient Egyptians were able to produce pulleys and strong ropes for block-and-tackle systems. Near the Valley Temple of Menkaure (4th Dynasty), a semicircular bearing stone with three guide grooves for ropes was discovered (Fig. 4b).[23] Pulleys made of hardwood, stone or faience have survived from the Middle and New Kingdoms and the Byzantine period (Fig. 4c–e).[24] Even an early Old Kingdom craftsman would have had little difficulty producing a roller or sheave made of hardwood, stone, or

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21 Ref 23, p 28, figs 5.2, 5.3.

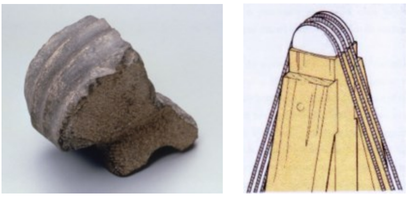
22 Cf. Ref 18, p 15; Ref 29, p 135.

23 MFA 11.34910.

24 Ref 21, pp 8–9; MMA 2.20.41; MMA 3.15.1118; Ashmolean Museum AN1929.219; Musée du Louvre E 1850, E 1854 (N 1634); MFA 13.3831 (without axle hole); Rijksmuseum van Oudheden, AH 92.

arsenical bronze with one or more grooves and a copper axle (either a solid copper rod or a copper tube force-fitted onto a wooden rod[25]).[26] Egyptian copper ores naturally contained lead, iron, arsenic and antimony.[27] The copper smelted from these ores, often with a deliberately increased arsenic or lead content (arsenical bronze, leaded copper), was very tough, lubricious and abrasion-resistant.[28] Strong ropes or leather straps are suitable for mounting pulleys on a beam or on the load. Ancient Egyptian ropes made of palm fibers, papyrus, or hemp had a high tensile strength.[29]

a) Modern pulley made of steel



b) Rope bearing stone,
granite, 4^{th} Dyn., Giza

c) Double-groove pulley,
wood, 12^{th} Dyn., el-Lisht

d) Cylindrical pulley,
wood, 18^{th} Dyn., Deir el-Medina

e) Ready-to-use pulleys,
wood, 3rd–5th century CE, Egypt

Fig. 4: Modern and ancient Egyptian pulleys

2.2 Suggestion

The idea that the Egyptians in the early Old Kingdom used systems similar to block and tackle systems is not new. Evidence suggests that large cylindrical rollers, operating on

[25] Such tubes have served as drill bits since the Naqada II period (Ref 30, pp 12-13, fig 1.5).

[26] For metal and stone processing technology see Ref 30, pp 25–73, 139–150; Ref 31.

[27] Ref 32, pp 32–33.

[28] Ref 30, pp 25–73; Ref 31; Ref 33. Tin bronze was still rarely used in the Old Kingdom (Ref 32, p 33).

[29] Ref 15, p 36–38; Ref 23, p 16.

the same mechanical principle as a block and tackle, were used to lower the portcullis blocks in the portcullis chambers of the pyramids of Khufu and Menkaure at Giza.[30] When people talk about a block and tackle, they almost always have the vertical lifting of a load in mind. To lift the masonry blocks of a pyramid, a crane-like mast with a counterweight would have been required on each finished step of the core masonry.[31] However, a block and tackle can also be used to haul loads on a sledge up an ascending ramp or across the working plateau of a pyramid under construction.

In 2018, a team of researchers discovered a ramp flanked with stone steps and rows of postholes, leading from the open-cast pit to the surrounding area of a 4th Dynasty[32] travertine quarry at Hatnub (Kom el-Nana, Eastern Desert). They suspect that the posts were used to attach ropes.[33]

My alternative suggestion is as follows (Fig. 5):

A solid wooden beam with two separate block-and-tackle systems is anchored behind two posts. Each block and tackle has four to six movable pulleys.[34] The load (stone block plus sledge) is evenly distributed between the two block-and-tackle systems. The traction force per individual on each block and tackle (F_i in newtons), can be calculated using the formula $F_i = \frac{\frac{F_W}{2}}{N_{rs}} \cdot (\sin\alpha + \mu_k \cdot \cos\alpha)$ where F_W is the weight force of the load in newtons (approximately equal to the weight in kilograms multiplied by 10), N_{rs} is the number of rope segments per block and tackle, α is the slope angle of the ramp in radians, and μ_k is the dimensionless coefficient of kinetic friction. In the spiral ramp proposed by Mark Lehner (1985), the slope angles range from 6° to 18° (0.1 to 0.3 rad).[35] The reported μ_k values of wood on wood, wood on lubricated wood, and wood on moist sand are 0.2–0.6, 0.15–0.2, and 0.3–0.5, respectively.[36]

30 Ref 15, pp 27–33; Ref 34; Ref 35, pp 44–48, 126–128, plt 7.

31 If the outer casing stones were laid at the same time as the stone blocks of the core masonry (Ref 18, pp 20, 27; Ref 23, p 5), the step would no longer exist once the layers are completed.

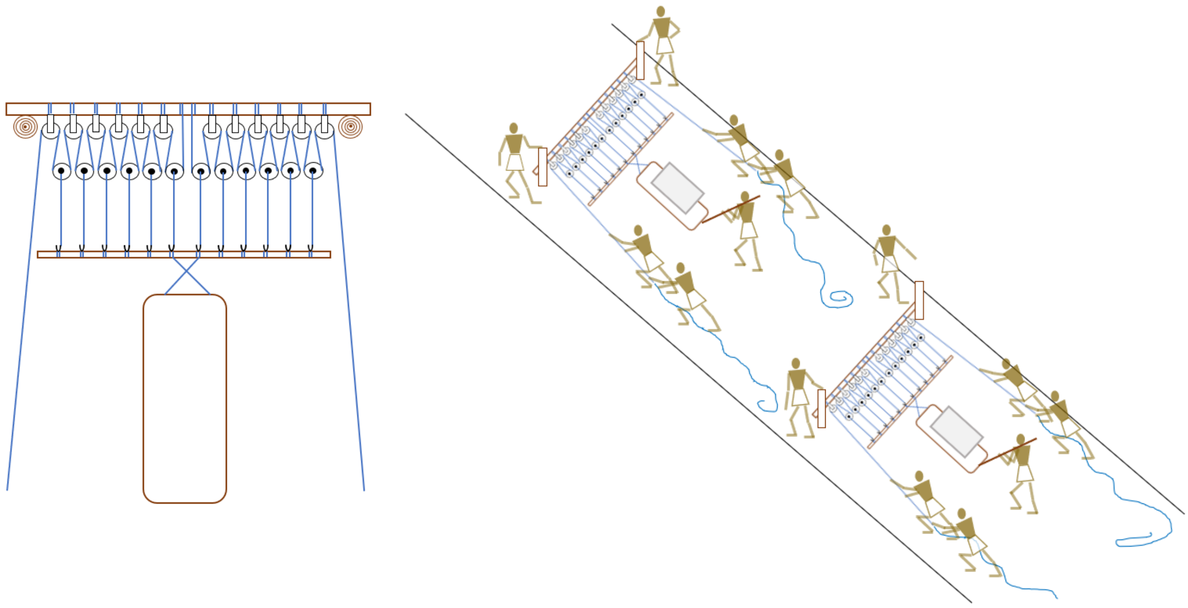
32 Dated by inscriptions.

33 Ref 36; Ref 37.

34 The upper load limit for hardwoods, such as sycamore, and Nile acacia wood is 1,000 and 750 kg/cm², respectively (Ref 21, p 9).

35 Ref 19, p 130, fig 5.

36 Assuming smoothed wood and constant speed: Ref 3, p 3, fig 5; Ref 4, p 57, fig 3; Ref 7, p 15; Ref 14, p 40; Ref 23, p 15; Ref 28, p 468, fig 2; Ref 30, p 196; Ref 38, pp 32–57. F. Müller-Römer reported exceptionally low μ_k values of 0.01–0.12 for wooden runners on lubricated timbers (Ref 15, p 39 [quoting Stöcker]; Ref 21, p 6).



a) The sledge is hauled on two separate block-and-tackle systems, each with six movable pulleys and 12 rope segments. The beam with the fixed pulleys is anchored behind two stable posts (top view; blue indicates the ropes).

b) Hauling teams on a construction ramp (a slipway has been omitted in the drawing)

Fig. 5: Hauling a load on a sledge up an ascending ramp with mobile block-and-tackle systems

The table below lists the values for F_i for a 2.5-ton load[37] under various conditions. F_i increases or decreases percentage-wise with a higher or lower load weight. When each block and tackle is pulled by two men, the traction force per man is halved. Pulling happens synchronously on command. One worker ensures that the sledge stays on track. After managing a section of the ramp, two workers carry the crossbeam with the fixed pulleys to the next pair of posts above. Meanwhile, chocks prevent the sledge from sliding backward. The workers on the pulley beam can alternate with the workers on the ropes.

When considering realistic F_i values, it should be taken into account that the haulers also carried their own body weight uphill, and that each time a sledge was set in motion from rest, a higher friction force had to be overcome compared to steady movement (coefficient of static friction, $\mu_s > \mu_k$).

[37] The density of limestone is approximately 2.5 tons per cubic meter. The volumes of the pyramid core blocks range from 0.4 to 1.2 cubic meters weighing 1 to 3 tons (Ref 18, p 26; Ref 23, p 18).

Table 1: Traction force per man (F_i) for a 2.5-ton load hauled on two block-and-tackle systems

α (°)	α (rad)	μ_k	N_{rs} of each block and tackle	F_i (newtons)	
				1 man on each block and tackle	2 men on each block and tackle
6	0,105	0,15	1*	3171	1586
6	0,105	0,15	8	396	198
6	0,105	0,25	8	552	276
6	0,105	0,5	8	940	470
6	0,105	0,15	12	264	132
6	0,105	0,25	12	368	184
6	0,105	0,5	12	627	313
18	0,314	0,15	1	5644	2822
18	0,314	0,15	8	706	353
18	0,314	0,25	8	854	427
18	0,314	0,5	8	1226	613
18	0,314	0,15	12	470	235
18	0,314	0,25	12	569	285
18	0,314	0,5	12	817	409

* Simple rope deflection pulley.

α: Slope angle; μ_k: coefficient of kinetic friction; N_{rs}: number of rope segments; F_i: traction force per man. Red figures: F_i > 400 newtons (assumed limit of tolerability for a hauler exposed to rhythmic stress and several hours of work per day).[38]

The figures in the table indicate that at least two haulers pulled together on each block and tackle, and that the μ_k value in the sledge track was optimized to 0.25 or less. This could have been achieved by covering the track with a continuously moistened layer of clay mud ("as slippery as ice"[39]) or by preparing a slipway of tallow- or mud-lubricated beams[40]. However, a slope with an angle greater than 8° that is too slippery poses a risk

38 The estimated F_i values for hauling tasks in ancient Egypt range from 200 to 800 newtons (Ref 23, p 17; Ref 30, p 196; Ref 38, pp 32–57; Ref 39, pp 20–24; Ref 40, p 64).

39 According to J. Vercoutter in Ref 10, pp 62–73. See also Ref 21, p 6; Ref 30, p 196.

40 Ref 21, p 6; Ref 23, p 15 (quoting Cotterell and Kamminga); Ref 41, pp 208–210; Ref 42, pp. 265–267. Literature review in Ref 13, pp 278–279.

of the haulers losing control of the sledge, even when chocks are readily available.[41] Therefore, an ideal compromise between α and μ_k had to be found.[42] The haulers' feet also needed good grip beneath the sledge track.

Provided the ramp is stable and capable of supporting several hauling teams, the system is very efficient. Loaded sledges can be placed one behind the other on the ramp and moved forward in sections. Under ideal conditions, a team of seven men per sledge is sufficient (Fig. 5b), compared to a hauling team of at least 32 men without block and tackle.[43]. This method can also be used to turn a sledge in a corner of a spiral or zigzag ramp. For extremely heavy loads,[44] more than two complex block-and-tackle systems and/or pulleys with more than one rope guide groove would be necessary to multiply the number of rope segments.

Other unresolved problems include loading and unloading the sledges and fitting the blocks into the masonry. H. J. de Haan (2010) demonstrated that these tasks could be theoretically accomplished using wooden levers and piles of boards.[45] Cut-outs in some pyramid stone blocks for the levers seem to confirm this theory.[46] The slick moist gypsum mortar allowed the blocks to be adjusted to one another.[47]

No conclusive Old Kingdom block-and-tackle equipment was found. This is not surprising, as the majority of preserved ancient Egyptian objects are funerary objects. The former workshops and workmens' settlements near the pyramids of Giza have only been partially excavated because modern roads, agricultural areas, and residential areas now extend close to the Giza plateau. Experimental archaeologist Denys A. Stocks (2003) wrote:

> "Several important areas of ancient technology remain shrouded in mystery, particularly those concerned with stoneworking; our ability to assess the development of ancient Egyptian technology, despite finding many tools, artifacts and tomb illustrations of manufacturing processes, is frustrated by an incomplete knowledge of important crafts, and virtually no knowledge at all of significant tools missing from the archaeological record."[48]

This article does not speculate on the most appropriate type of ramp, nor does it calculate material consumption, total labor requirements, or energy consumption. These topics

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41 Ref 21, p 3; Ref 30, pp 197–198.

42 Therefore, the lowest μ_k value in the table is 0.15.

43 Ref 23, p 18.

44 See note 14.

45 Re 23, pp 23–25, 39, fig 4.9.

46 Ref 30, p 193; Ref 40, pp 71–72, 270–275.

47 Ref 5, p 45 (quoting Clarke and Engelbach); Ref 30, pp 195–196; Ref 43, p 284. D. A. Stocks has described one possible method for creating the precise heading joints between the observable blocks (Ref 30, pp 191–194).

48 Ref 30, p 2.

have already been covered in a large body of literature.[49] The article aims to demonstrate that the effort required to haul heavy-duty sledges up an ascending ramp or across the working plateau of an unfinished pyramid using the proposed mobile block-and-tackle systems can be reduced by more than 90%, and that the Egyptians of the early Old Kingdom were capable of manufacturing the necessary equipment. Proof-of-concept experiments by experimental archaeologists are warranted.

Abbreviations

BAR: British Archaeological Records; BM: British Museum; CC: Creative Commons; CE: Christian era; Dyn.: dynasty; F: traction force; F_w: weight force; F_i: traction force per man; Fig.: figure; JE: Journal d'Entrée (du Musée du Caire); JAS: Journal of Archaeological Science; JAEA: The Journal of Ancient Egyptian Architecture; JAEI: Journal of Ancient Egyptian Interconnections; Kush: Kush – Journal of the Sudan Antiquities Service; MDAIK: Mitteilungen des Deutschen Archäologischen Instituts, Abteilung Kairo; MFA: Museum of Fine Arts, Boston; MIFAO: Mémoires publiés par les membres de l'Institut Français d'Archéology Orientale du Cairo; MMA: The Metropolitan Museum of Arts, New York; N_{rs}: number of rope segments; OJA: Oxford Journal of Archaeology; p/pp: page(s); plt: plate; Ref: reference; SAK: Studien zur altägyptischen Kultur; Vol: volume; α: slope angle; μ_k: coefficient of kinetic friction; μ_s: coefficient of static friction.

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[49] E.g., Ref 14; Ref 15; Ref 18; Ref 23.

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Image credits

Fig. 1: Relief in the tomb of Ti (5th Dyn., Saqqara): Drawing: Ref 1, plt 55 (CC 0).

Fig. 2: Relief in the tomb of Djehutihotep (12th Dyn., Deir el-Bersheh): Drawing: Ref 2, plt 12 (CC 0).

Fig. 3: Own drawing.

Fig. 4: a) Modern pulley. Photo: Zener, Singapore.

b) Bearing stone for ropes, 4th Dyn., Giza. Photo: Museum of Fine Arts, Boston, 11.34910, https://collections.mfa.org/search/objects/*/11.34910 (CC 0; accessed March 12, 2025). Drawing from Ref 44, p 211.

c) Double-groove pulley, 12th Dyn., el-Lisht. Photo: Ref 40, p 212.

d) Cylindrical pulley, 18th Dyn., Deir el-Medina. Photo: Ref 21, p 8 (CC 0).

e) Ready-to-use pulleys, Byzantine Period, Egypt. Left photo: Rijksmuseum van Oudheden (Leiden), AH 92, https://www.rmo.nl/en/collection/search-collection/collection-piece/?object=18292 (CC 0; accessed March 12, 2025). Right photo: The Metropolitan Museum of Art, New York, 20.2.40, https://www.metmuseum.org/art/collection/search/475047 (CC 0; accessed March 12, 2025).

Fig. 5: Own drawings.