We study the Dirichlet eigenvalue problem for the fractional sub-Laplacian $(-\triangle_{\mathbb{G}})^s$ on the homogeneous Carnot group $\mathbb{G} = (\mathbb{R}^n, \circ)$. Let $\Omega$ be a bounded open domain of $\mathbb{G}$ and denote by $\lambda_k$ $(:= \lambda_k(s))$ the $k$-th Dirichlet eigenvalue of the fractional sub-Laplacian operator $(-\triangle_{\mathbb{G}})^s$ on $\Omega$. We use the abstract theory of Dirichlet forms and heat semigroups to construct explicit estimates for the trace of the Dirichlet heat kernel of $(-\triangle_{\mathbb{G}})^s$ via a comparison of heat kernels. Based on these estimates, we give an explicit lower bound estimate for $\lambda_k$, which exhibits the optimal growth order of $k$. Then, we establish the Weyl's law for the spectral counting function $N(\lambda)$. In particular, under a certain geometric condition of $\Omega$, we also provide the reminder term estimate of the trace of the Dirichlet heat kernel and an explicit upper bound of $\lambda_k$ with optimal growth order of $k$.